CONSTRUCTION WASTE MANAGEMENT AT SOURCE: A BUILDING INFORMATION MODELING BASED SYSTEM DYNAMICS APPROACH

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OF THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE COLLEGE OF GRADUATE STUDIES

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Okanagan)

November 2013
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Abstract

Construction waste is considered a major contributor of solid wastes in municipal landfills. As per the Canadian construction industry, construction, renovation, and demolition (CRD) wastes constitute 27% of total municipal wastes disposed to landfills. Many researchers have stated that 75% of wastes generated by construction industries have residual value. They can be even recycled, salvaged, and/or reused. In such circumstances, construction wastes have to go for recycling, which is as costly and environmentally harmful as going for new material. Sustainable and practical solutions then have to: (i) minimize the construction waste at source during the project construction phase, and (ii) optimize the material usage of the ‘proposed construction’ in the design phase itself. To achieve both of these objectives, virtual construction techniques, which can forecast potential waste of a given project with cost and schedule variations, are required. However, there are only a few studies carried out to analyse the complex relationships among the design, rework, material management, and construction functions in waste management. The waste should be avoided at source by considering the entire life cycle performance of the project.

Building Information Modeling (BIM) is a relatively new and much unexplored area in construction waste management. BIM has immense potential with today’s computing power and technology. The aim of this thesis is to enhance use of BIM to minimize construction waste at source by micro-mapping objects and spaces with a novel use of dynamic simulation techniques and earned value management methods. System Dynamic Modeling (SDM) is an effective tool to analyse the pattern of changes in variables of a system over time. The use of the SDM enables projects to be managed more effectively with respect to waste management and policy assessment.

This thesis proposes a method of dealing with the complexity, interrelationships, and dynamics of Design-Bid-Build projects. Firstly, a BIM-Partnering approach for public construction procurement is presented with the aim to reduce construction waste right at source, early in the design stage. Then, a reinforcement cutting waste optimization technique integrated with BIM is presented. Values of major variables are extracted from BIM and its link with project and scheduling information. Finally, a dynamic model integrated with BIM; to minimize construction waste at source is presented. Three case studies were carried out to demonstrate the applicability of BIM, coupled with SDM, in project management and waste
minimization at source on its first go.

**Keywords:** Sustainability, Construction waste management, Building Information Modeling (BIM), System Dynamic Modeling (SDM), Waste reduction at source, Earned Value management.
Preface

Five journal papers have been published, submitted (under review), or are in preparation from the research presented in this thesis. Complete references are provided below:


A part of Chapter 3 has been published as paper 1. I wrote this paper, while Dr. Hewage provided a critical review with suitable feedback and finalized the manuscript. A version of Chapter 4 has been submitted as paper 3. I wrote this paper, while Dr. Hewage provided review, feedback, and finalized the manuscript. Two manuscripts (4 and 5 as mentioned above) from the content of Chapter 4 are in preparation for publication. Dr. Hewage is providing his feedback on these manuscripts. Chapter 5 has already been published as paper.

This research work was carried out with the approval of Behavioral Research Ethics Board, University of British Columbia, Okanagan (UBC BREB NUMBER H10-01000).
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List of Symbols

\( A_{ij} \)  Number of bars of length \( l_j \) present in pattern number \( i \)
\( c \)  Clear cover to reinforcement
\( C_i \)  Utilized length of pattern number \( I \)
\( d_b \)  Diameter of bar
\( d_j \)  Number of bars of length \( l_j \) that are needed to satisfy the demand
\( dt \)  Fraction of time
\( E \)  Energy
\( f_c \)  Compressive strength of concrete
\( h \)  Hook length (i.e. \( l_{hb} \))
\( i \)  Integer value of \( L \)
\( k \)  Boltzmann’s constant
\( I \)  Total number of patterns generated
\( l \)  Market length of rebar
\( l_{hb} \)  Basic hook length
\( L \)  Total lengths required
\( L_e \)  Cut-off length at the end
\( L_{si} \)  Standard length if pattern number \( i \) is cut
\( N \)  Number of market lengths required
\( s \)  Splice length
\( S \)  Beam length (continuous or support to support)
\( t \)  Time
\( T \)  Temperature
List of Abbreviations

1D  One Dimension
2D  Two Dimension
3D  Three Dimension
4D  Four Dimension
5D  Five Dimension
ACWP  Actual Cost of Work Performed
AC  Actual Cost
AEC  Architect/Engineer/Contractor
AIA  American Institute of Architects
API  Application Program Interface
AT  Actual Time
BAC  Budget At Completion
BCWP  Budgeted Cost Of Work Performed
BCWS  Budgeted Cost Of Work Scheduled
BIM  Building Information Modeling
BSI  British Standard Institute
C&D  Construction and Demolition
C/SCSC  Cost Schedule Control System Criteria
CAD  Computer Aided Design
CCA  Canadian Construction Association
CDN  Canadian Dollar
CIDA  Construction Industry Development Agency
CM  Construction Manager
CNC  Computerized Numerically Controlled
COAA  Construction Owners Association of Alberta
COBIM  Common BIM
CPI  Cost Performance Index
CPM  Construction Project Management
CRC  Cooperative Research Centre Australia
CSA  Canadian Construction Association
CSI  Construction Specifications Institute
CV  Cost Variance
D-B  Design-Bid
D-B-B  Design-Bid-Build
D-B-F-O  Design-Build-Finance-Operate
D-B-O  Design-Build-Operate
EAC  Estimate At Completion
EBP  Early BIM Partnering
ECI  Early Contractor Involvement
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ES</td>
<td>Earned Schedule</td>
</tr>
<tr>
<td>ETC</td>
<td>Estimate To Complete</td>
</tr>
<tr>
<td>EV</td>
<td>Earned Value</td>
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<tr>
<td>EVM</td>
<td>Earned Value Management</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>GIS</td>
<td>Graphical Information System</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating Ventilation Air-conditioning Cooling</td>
</tr>
<tr>
<td>IBC</td>
<td>Institute for BIM in Canada</td>
</tr>
<tr>
<td>IEAC</td>
<td>Independent Estimate At Completion</td>
</tr>
<tr>
<td>IFC</td>
<td>Industry Foundation Class</td>
</tr>
<tr>
<td>INIT</td>
<td>Initial value</td>
</tr>
<tr>
<td>IPD</td>
<td>Integrated Project Delivery</td>
</tr>
<tr>
<td>IT</td>
<td>Information Technology</td>
</tr>
<tr>
<td>LEED</td>
<td>Leadership in Energy and Environmental Design</td>
</tr>
<tr>
<td>LOD</td>
<td>Level Of Detail</td>
</tr>
<tr>
<td>MEP</td>
<td>Mechanical Electrical Plumbing</td>
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<tr>
<td>MPS</td>
<td>Model Progression Specifications</td>
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<tr>
<td>NBS</td>
<td>National Building Specifications</td>
</tr>
<tr>
<td>OCCS</td>
<td>OmniClass Construction Classification System</td>
</tr>
<tr>
<td>PCCBC</td>
<td>Public Construction Council of British Columbia</td>
</tr>
<tr>
<td>PD</td>
<td>Planned Duration</td>
</tr>
<tr>
<td>PDCS</td>
<td>Project Deliveries and Construction Strategies</td>
</tr>
<tr>
<td>PERT</td>
<td>Program Evaluation and Review Technique</td>
</tr>
<tr>
<td>PMB</td>
<td>Performance Measurement Baseline</td>
</tr>
<tr>
<td>PPP</td>
<td>Public Private Partnership</td>
</tr>
<tr>
<td>PWGSC</td>
<td>Public Works and Government Services Canada</td>
</tr>
<tr>
<td>RCD</td>
<td>Reed Construction Data</td>
</tr>
<tr>
<td>RFP</td>
<td>Request For proposal</td>
</tr>
<tr>
<td>SD</td>
<td>System Dynamics</td>
</tr>
<tr>
<td>SDM</td>
<td>System Dynamic Modeling</td>
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<tr>
<td>SPI</td>
<td>Schedule Performance Index</td>
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<tr>
<td>SSC</td>
<td>Stipulated Sum Contract</td>
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<tr>
<td>SV</td>
<td>Schedule Variance</td>
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<tr>
<td>TFT</td>
<td>Total Factor Productivity</td>
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<tr>
<td>UPC</td>
<td>Unit Price Contract</td>
</tr>
<tr>
<td>USGBC</td>
<td>United States Green Building Council</td>
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<tr>
<td>WBDG</td>
<td>Whole Building Design Guide</td>
</tr>
<tr>
<td>WP</td>
<td>Work Performed</td>
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</table>
Acknowledgements

Working as a PhD student in the University of British Columbia, Okanagan (UBCO) has been a wonderful and challenging experience for me. I would like to express my sincere gratitude to the faculty members and staff at UBCO. Firstly, I wish to express immeasurable appreciation and deepest gratitude to my supervisor, Dr. Kasun N. Hewage, for his continuous help and support. He has worked vigorously in making ideas and giving proper shape in the research proposal to final report write-up. His intellectual skills, valuable comments, timely advice, and intimate supervision have been instrumental for smooth and successful completion of my thesis. I would like to express profound appreciation to Dr. Rehan Sadiq, who has kept following my progress and provided constructive advice and moral support during my tenure as a PhD student at UBCO. I would like to thank Dr. Sharia Alam and Dr. Dwayne Tannant, who are also in my PhD committee, for their accessibility, useful suggestions and fruitful recommendations.

I would like to acknowledge the contributions of Dr. Kallol Mondal of IIT Kanpur for providing advice and help with the final report write-up.

I would also like to acknowledge Phil Long for sharing valuable information related to the engineering building and RCMP project. I wish to acknowledge Dominion Fairmile Ltd., Maple Reinders Inc., and Aplin & Martin Consultants Ltd. for their support and assistance in the case studies carried out in the present thesis. I appreciate all financial support for my PhD study, including, NSERC General Revenue Fund, University of British Columbia PhD Tuition Fee Okanagan Award, and StudentAidBC.

Most importantly, I would like to give my innermost thanks to my parents, who are my source of inspiration all the time. Their unfathomable love and affection have always allowed me to overcome all the obstacles experienced on my way to be the recipient of such an honor of getting PhD. My deepest appreciation goes to my wife, Shikha, for her utmost sacrifice, boundless support, and constant encouragement. Acknowledgement would be incomplete if I don’t mention encouragement received from Anshul, my son, and Ashi, my daughter. In fact, my son wanted me to go for a PhD. Finally, I feel content that I have kept his wish. At the end, I would like to acknowledge exceptional support of my brother, Mukesh. I have no other words to express his contribution in shaping my carrier all throughout my life. I can only cherish his presence. Thank you, brother.
To My Parents
Chapter 1 Introduction

This thesis addresses methods to minimize construction waste at source for enhancing virtual construction techniques and enabling better understanding of dynamics of construction environment. This would further improve decision making in effective project management. The current Chapter gives a general introduction. It first provides brief background information followed by motivation and objectives of this research. This Chapter is intended to lay the conceptual groundwork for readers to understand the significance of the present research. Finally, the structure of the thesis is described.

1.1 Background

Construction waste management is considered to be a practice followed for minimization of wastes originating from demolition, changes in design, rework, trimming, etc., and finally diverting the wastes for their re-use in the construction process. Since wastes during construction ultimately end up in landfills, construction waste management would also minimize the burden of landfill loading.

Environmental sustainability has become a major concern for many industries in Canada. Sustainable development practices are well recognized and all governments (local and federal) in Canada are trying to enforce these practices. However, Environment Canada has estimated 9 million tons of construction and demolition wastes on an annual basis in Canada (The Canadian Construction Association, 1992). This amount accounts for 1/3 of the country’s solid waste stream, and therefore, construction waste management should be considered a priority.

Carbon reduction efforts are affected by waste management through the impact of one or more of the following:

- Consumption of energy related to the manufacturing, using, transporting and disposal of the waste materials
- Release of gases such as carbon dioxide during the process of manufacturing of metals like steel and aluminum
- Emission of gases like methane from the landfills due to disposal of wastes

The construction industry, like many other industries, needs to adopt advancements in technologies to overcome adverse impacts of construction waste, thereby reducing carbon emissions associated with buildings.
The Department of Environment and Resource Management (DERM, 2011) reported that construction activity generated approximately 8.5 million tonnes of wastes deposited to Australian landfills, whereas, as per the European Environment Agency (2010), more than 30% of the wastes coming to landfill in UK consist of construction wastes. Rogoff and Williams (1994) stated that construction waste constitute 29% of the solid waste in the USA. According to Cotton et al. (1999), a major health hazard is associated with uncollected solid construction wastes. Moreover, municipal wastes are considered to be a potent cause of serious health hazards. Poon (1997) noticed that a large share of all types of solid wastes consisted of construction wastes.

All the above studies demonstrated that a large amount of waste is generated by the construction industry. With the objective of having better control over construction wastes, previous researchers have developed various management methods:

- Sorting out specific categories of wastes in order to adopt management techniques specific to those types of waste (Spivey, 1974).
- Employing sequential waste management methodologies in reduce, reuse, and recycling wastes; and disposing of wastes where the first three options are not possible (Chun et al., 1997; Faniran et al., 1998).
- Using environmental friendly construction methods such as applying pre-fabricated components, reducing the application of wet construction methods, and using large panel systems (Ho, 2001).
- Applying waste management methods as part of the project management process with genuine support from management (Shen et al., 2002).

Though construction waste management mainly focuses on reuse, recycling, and proper disposal of waste materials at landfills, the best and most efficient method for minimizing generation of waste is its reduction to eliminate many of the waste disposal problems (Begum et al., 2006). While the focus on reduction of waste has been negligible in previous years, application of waste reduction strategies at the source may be one of the best approaches in minimizing the intensity of the construction waste problem (Sammy et al., 2009). Therefore, in order to achieve the goal of reducing wastes associated with buildings, a novel way of thinking must be adopted.

Construction processes essentially involve complex and dynamic interactions among diverse variables, such as participant experience, physical attributes, resource procurement,
strategies, time and cost constraints, and management techniques (Lee et al., 2006). Errors in design and changes in the processes associated with construction are very common and among the causes of uncertainty in construction projects (Lee et al., 2003a). An unanticipated error could affect other activities associated with its functional relationships. The static approach in traditional construction planning and control tools is not very efficient in dealing with these problems (Lyneis et al., 2001). On-site waste generation is dynamic in nature and any change in scope of work during the construction process creates ‘rework’, which, in turn, generates more waste. However, literature on the prediction of construction waste generation and generation patterns due to design change and rework over the entire project life cycle are limited.

1.2 Research Objectives
This research aimed to minimize construction waste due to change in scope of work at source. The specific objectives of the present research are:

1. Study of ‘state-of-the-art’ waste management approaches and identify application of today’s computing power in the context of construction waste management
2. Develop an application of Building Information Model (BIM) for waste management of linear structural components
3. Develop a System dynamic model (SDM), which can predict construction waste at source, in integration with BIM
4. Develop a BIM-partnering framework for early design coordination in public construction procurement

1.3 Thesis Structure
The structure of this thesis is illustrated in Figure 1-1. Ideas put forward in each Chapter usually build the concepts in the following Chapters.

Chapter 1 is a general introduction and definition of problems and current status of construction waste management practices. It presents a preamble to justify the objectives of the current research.

Chapter 2 provides a comprehensive review of waste management methodologies used in the construction industry. It introduces the overview of construction procurement methods used and the application of Earned Value (EV) management. BIM, an innovative new approach to
building design and documentation, is presented as a potential waste management tool along with its specific application in cost analysis. This Chapter elaborates on the application of SDM in waste management and BIM as a virtual construction management tool.

Both Chapter 3 and Chapter 4 address the application of BIM in waste management at source. Chapter 3 demonstrates an approach to optimize linear structural waste at source using the BIM process. A brief introduction to optimization techniques and algorithms used in optimization of linear objects is presented in appendix C. In Chapter 4, an integrated BIM-SDM model to minimize construction waste at source using an EV management concept and a crew based construction productivity approach is formulated. The method put forward demonstrates the use of BIM’s virtual information into SDM, through feedback loops.

Chapter 5 suggests a BIM-partnering approach to involve the Architect/Engineer/Contractor (AEC) early in the BIM-design process. This approach is focused on faster adoption of BIM in the procurement of publically funded construction projects.

Finally, conclusions are drawn and recommendations for future research are provided in Chapter 6.
1.4 Hypothesis

Literature review indicates that there is a need for a methodology to reduce construction waste at the source of generation. The research question of this study was “how virtual construction technique would be used to predict and reduce the construction waste at source of generation?” Following test hypotheses were derived from the above research question:

H1: “BIM data generated during the design phase, through virtual simulation of a construction process, can be used for dynamic analysis, before the start of the construction work, to predict cost and time overrun and potential amount of waste.”

H2: “If coordinated BIM process is performed by involving construction team into the design phase, then construction waste can be reduced at source by application of optimization techniques.”

Hypothesis-1 was addressed by creating a system dynamic model of the construction process, and analysis of the process by input of virtual BIM data. Earned Value (EV) management
technique was used to predict the cost and time variables.

Hypothesis-2 was addressed by applying optimization algorithm with the BIM coordination methodology, and it was tested on minimization of rebar waste of reinforced concrete structural members. A BIM-partnering framework was also developed to involve contractor into the design process of a design-bid-build procurement, and it was tested over a public building project.

1.5 Methodology

Following methodology (Figure 1-2) was adopted to achieve the objectives mentioned in section 1.2. This research used different techniques to collect data, such as interviews, questionnaire surveys, and field observations. The survey questionnaire is attached in Appendix E. A pre-review of the questionnaire was done through unstructured interviews with four senior engineers in building construction projects. The questionnaire survey was conducted to assess the status of the use of BIM in the design coordination process. Questions were asked about the organization, the individual work and experience, and the use of BIM within the organization. Questionnaire survey was conducted through emails, telephone calls, and individual meetings with 46 firms, and 24 responses were received. Field data were mainly collected from three construction sites during the projects’ construction phase, and each project was treated as a separate case study.

1.5.1 Methodology: Objective 1

The most current literature was thoroughly reviewed throughout the research. Various concepts of construction waste quantification, causes, types of wastes, and methods of disposal including its impact on the environment were reviewed in detail. An in-depth study of construction procurement methods and the latest developments in management techniques were also reviewed to identify challenges in construction waste management. Based on speculations, a further study in the areas related to BIM and SDM were performed to arrive at a strategy for waste minimization at source.

Qualitative and quantitative data analysis were performed using surveys and field observations to achieve objectives 2, 3, and 4:
Figure 1-2: Flowchart of the methodology used in the research
Five interviews were conducted with the estimators and Computer Aided Design (CAD) operators of 5 construction projects. This provided information about the methods used to prepare cost estimates in the construction industry.

A market survey was conducted to study the CAD tools available for cost estimation and their applications in the material management process. This was performed through:

a) Questionnaire survey with 46 major engineering firms,
b) Online survey of products available and their task performing features,
c) Interviews of architects from 18 engineering firms in the area.

1.5.2 Methodology: Objective 2

A thorough desk study of linear optimization techniques and their application in waste minimization was performed. Current methods of structural reinforcement detailing and its placement at site was studied. An on site study of coordination in design and construction of structural members was conducted on 5 projects. A market and desk top survey was conducted to obtain data about availability of size and length of rebars. To assess trim loss of reinforcement bars:

(i) Conducted open ended interviews with the structural engineers of 5 projects and investigated the design and construction procedures followed.

(ii) Field investigations were performed to study the method of structural reinforcement placement on two construction projects from 2010 to 2011.

(iii) Onsite records were studied to perform a quantitative analysis of structural reinforcement trim loss.

(iv) Conducted open-ended interviews with architects of 5 firms to study the waste management strategied adopted during design phase.

1.5.3 Methodology: Objective 3

To achieve objective 3, a system dynamics (SD) model was developed based on the study and data collected as mentioned in objective 1 and objective 2. This SD model was then run as a base case scenerio to check for its simulation results and the model performance analysis. Finally, this SD model was fed with the virtual data collected from the BIM model of the project and compared with the results of the SD model obtained through field data. This was done to check the SD model’s ability to successfully generate simulated results in
the initial stage of the project to predict the wastes, and cost and time overruns in the virtual construction environment.

Field investigations were carried out on an educational building construction project to analyze the complexities and inter-relationships among the variables, to identify typical ones for the simulation of the waste management process. This helped to define the boundary of the system modeling. The parameters were further fine-tuned to match up with the characteristics observed in the field. The detailed field study consisted of the following:

(i) Investigated the process of revising the design/drawings, when a change in scope of work occurred.

(ii) Conducted open-ended interviews with the project manager and construction team of 3 projects and investigated the time delays in receiving revised designs. Also studied the factors contributing to the delays.

(iii) Field investigations were performed to study the effects of changes on material procurement systems.

(iv) Direct onsite observations were conducted to study the dynamics of the parameters and their relationships.

(v) Onsite records were studied to perform quantitative analysis.

(vi) Field observations were performed on three different construction projects undertaken by the firms: (i) Aplin and Martin, (ii) Dominion Fairmile, and (iii) Maple Reinders in British Columbia, Canada from 2010 to 2012. These data is utilised in Chapter 4, which is on the system dynamic modeling of the construction process.

1.5.4 Methodology: Objective 4

Coordination work was done on a commercial construction project site with the project team to develop the BIM design process and the following hands-on activities were undertaken:

(i) Assisted consultant's design team in creating and maintaining the Architectural BIM model.

(ii) Created 2D drawings from the BIM model and checked the outputs with originally created contract drawings.

(iii) Prepared cost estimates from the BIM model and checked their accuracy with the manually worked out substantive estimate.
(iv) Worked with project team members to establish the specific design guidelines and model detailing levels to aid the electronic 3D design coordination process.

(v) Integrated the 3D models to conduct design coordination meetings by working with different 3D models and maintained a digital archive.
Chapter 2 Background

This Chapter presents a comprehensive literature review and relevant knowledge comprised of research done in construction waste management and application of system dynamics (SD) in the waste management area. The following section begins with a review of construction waste and its quantification followed by the application of simulation techniques. A literature review on today’s computing power and BIM is performed along with algorithm techniques applied to construction waste management.

2.1 Construction Waste

Responsible management of construction waste at site is a critical component of sustainable building. Disposal of construction waste activates a sequence of adverse effects, such as damage of useful property and generation of greenhouse gases. There are always environmental issues associated with producing new materials rather than using existing materials (WBDG, 2010).

2.1.1 Concept of waste

Ford (1926) suggested that focus on the waste management should be on waste prevention. Skoyles (1976) separated waste into two categories: direct and indirect material waste. A complete loss of material due to severe damage or physical loss was categorized as direct waste. The material wastes, that created only monetary loss, were termed indirect wastes - for example, waste due to increase in thickness of concrete slab from that specified by the structural design. According to the lean production definition as suggested by Koskela (1992), waste is associated mainly with concept of the process and the operation. A process is simply a combination of sub-processes that converts an input into an output. These sub-processes are also conversion processes. Ohno (1988) defined the concept of waste as the use of resources that did not add value to the final product. Womack et al. (1996) described waste as any human activity that absorbed resources and not created value to it. The following are considered conditions warranting rectification: production of unwanted items, useless process steps, unnecessary movement of employees, and unwanted waiting period for further activities. There are also other categories of waste, such as (i) accidents, (ii) working under unfavourable conditions (Koskela, 2000), (iii) design of least user-friendly products (Womack et al., 1996), (iv) unwanted capital investment (Monden, 1983), and (v) vandalism and theft (Bossink et al., 1996).
For the construction industry, waste was defined by Formoso et al. (2002) as, “any kind of loss of resources that generate direct or indirect costs but do not add any value to the final product from the point of view of the client”. These resources were defined as time (labour and equipment), materials, and capital or any kind activities.

2.1.2 Major causes of construction waste
The literature review shows that critical categories such as design change and/or error, defective work and rework, lack of proper material management, and poor coordination in operation and supervision, can contribute to considerable waste in a construction project (Table 2-1).

Literature reported that Skyoles (1976) first conducted extensive investigation on material wastes in the building industry at the Building Research Establishment UK on data obtained from 114 building sites. This study investigated both direct and indirect wastes. He broadly classified the main causes of waste mainly into two categories as unavoidable waste (or natural waste) and avoidable waste. The cost of avoidable waste was found to be higher than the cost to prevent it, while the investment necessary to reduce unavoidable waste (or natural waste) was found to be higher than what the economy produced. Direct waste of 37 materials from 68 sites, most consisting of residential building projects were measured (Skoyles, 1976). The range of percentage materials wasted was from 2% to 15% in weight, relative to the amount of materials estimated by design. This study mainly concluded that:

- The estimated loss was much higher than was estimated;
- The quantity of wastage produced was extremely variable, with a relatively low quantity at some sites. This suggested that much of the existing waste was avoidable;
- One of the main causes of waste was identified as mismanagement of materials at site;
- The more likely cause of waste was by a combination of events and not by a single incident.

A study was first carried out by Pinto (1989) on material wastes in Brazil on an 18 storey residential building project. Based on the well-kept records of materials supply and use, both direct and indirect wastes were estimated for 10 building materials. He found that the range of material waste was from 1% to 12% by weight to the amount of materials as per the design. The overall waste was found to be 18% by weight of purchased materials. This added
6% more waste to the above range of 1% to 12% waste. Picchi (1993) monitored the amount of waste removed from three residential building sites during the period between 1986 and 1987. He estimated the waste percentage to be between 11% and 17% of the expected weight of the building materials, amounting to between 0.095 and 0.145 t/m².

Table 2-1: Summary of Major Causes of Construction Waste

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Design (Scope)</th>
<th>Procurement</th>
<th>Error</th>
<th>Operation</th>
<th>Supervision</th>
<th>Labour</th>
<th>Residual related</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skoyles 1976</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<td>Pinto 1989</td>
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<td>HK Construction Asso.1993</td>
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<td>Galvian et al. 1994</td>
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<td>Bossink et al.1996</td>
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<tr>
<td>Faniran et al.1998</td>
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<td>Jayawardane 1998</td>
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<td>Forsythe 1999</td>
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<tr>
<td>Formoso et al. 2002</td>
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<tr>
<td>Ekanayake et al. 2004</td>
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<tr>
<td>Wan et al. 2009</td>
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</tbody>
</table>

(Adapted from Wan et al., 2009)

Research was conducted by The Hong Kong Polytechnic and Hong Kong Construction Association (1993) with an aim to reduce the demand for final disposal areas by reduction of waste at source. A waste monitoring process on thirty-two construction sites was conducted to focus on the most likely waste being generated, such as bricklaying, concreting, ceramic tiling and plastering. The lack of control of materials usage by contractors was concluded as one of the main reasons for wastage. The data related to concrete waste and the relative importance of six different materials (steel reinforcement, bricks and blocks, mortar, premixed concrete, wood, and ceramic tiles) was only presented in the final report. Fourteen sites were monitored for waste of premixed concrete, and waste ranged from 2.4% to 26.5% with an average of 11%.

Five homes at four separate construction sites from July to August 1992 were observed by Gavilan and Bernold (1994) in an empirical study. Three processes analyzed were: (i) masonry foundations, (ii) timber frames, and (iii) sheetrock drywall. The investigation of main causes of wastes was classified according to the sources and based on a model that described the flow of solid waste in building sites. Residual scrap resulting from cutting
materials such as sheetrock panels, dimensional lumber, bricks, and blocks was found as one of the major sources of waste. Much of the waste was comprised of wood, which, as non-reusable consumables, aided in the production process but did not end up as a final product.

A research project pertaining to the measurement and prevention of construction waste was conducted in the Netherlands by Bossink et al. (1996) for meeting sustainability requirements. Five house-building projects were monitored between April 1993 and June 1994 to measure the waste from seven materials. All material waste was sorted and weighed during the study. The range of amount of direct waste was between 1% and 10% of the weight of the purchased materials. The main causes were identified based on brainstorming sessions involving contractor representatives. These were mostly related to poor material handling, transportation and storage as well as pre-construction processes such as design and material supply.

A survey conducted by Faniran et al. (1998) revealed similar results by categorizing typical sources of construction debris into (i) design change, (ii) design error, (iii) leftover material scrap, (iv) packaging and non-reclaimable consumables, and (v) poor weather. Jayawardane (1998) concluded in a pilot study conducted in Sri Lanka that improper management of sites including material handling, supervision, and concerns of labour were the sources of a considerable amount of construction waste.

A model to analyze the impact of waste in the cost of its removal and disposal, including cost of project, was proposed by Forsythe et al. (1999). Waste data obtained from an empirical study of 15 house-building sites for six building materials in Australia was used in this model. This study showed material waste that ranged from 2.5% to 22% by weight. Quantification of measured waste was based on interviews with representatives of different trades, amount of materials effectively delivered on site, and according to available documents.

Formoso et al. (2002) carried out research studies in Brazil to measure the material waste and identify its main causes. He suggested a number of guidelines for further work to address the implementation of waste control in the construction industry:

- Both financial and nonfinancial waste measures must be used concurrently to support strategic decision making and at operational control level.
- Waste related to other resources, such as labour, equipment, and capital must be
considered to include waste in a broader sense.

- People involved in processes that precede production, must be involved in the corrective actions of design, planning, and material supply.
- Production planning and control processes should have a fully integrated waste control plan.

Based on application of multi-attribute value techniques under procurement, material handling, design, and operation related areas, Ekanayake et al. (2004) suggested that design was an essential contributor to the reduction of construction waste.

A study based on a survey to identify the sources of waste at each stage of electrical and mechanical installations in projects such as buildings, tunnels, or dams was conducted by Wan et al. (2009) in Hong Kong. The principal findings were (i) design changes, (ii) poor coordination, and (iii) variations or change orders and rework resulting in a high volume of construction waste.

The above-noted studies indicate that construction waste can be reduced by improving the entire construction cycle process. Meanwhile, it is acknowledged by most of the researchers that design has a major influence on construction waste (Table 2-1).

### 2.1.3 Rework due to design Changes

Rework is defined in many ways within the construction industry. It can be defined as “the process by which an item is made to conform to the original requirement by completion” (Ashford, 1992) and “doing something at least one extra time due to non-conformance to requirements” (CIDA, 1994). Rework has also been defined as the “unnecessary effort of redoing a process or activity that is incorrectly implemented for the first time” (Love and Heng, 2000).

Others have defined rework specifically for field operations as “activities in the field having been done more than once in the field or activities, which remove work previously installed as part of the project” (Rogge et al., 2001). Another definition of field rework is the “total cost of redoing work in the field regardless of initiating cause” (Fayek et al., 2003).

Various sources of rework have been recognized in the construction industry. Fayek et al. (2003) suggested a fishbone diagram (Figure 2-1), which showed taxonomy of rework consisting of five main sources with two levels of categories in the construction project:
(1) capability of human resource, (2) communication and leadership, (3) engineering (4) scheduling and construction planning, and (5) supply of equipment and material. Furthermore, the secondary level of Engineering and review category was mainly described as ‘change in scope of work’ due to changes suggested by owner, late design changes, and errors and omissions.

Figure 2-1: Expanded fishbone diagram of rework causes (Fayek et al., 2003)

Figure 2-2 shows the percentage of the first level contributions to rework. It shows that 50% of causes of rework occur within scheduling and design planning, while budgeting and programming contribute 27%, and review of design is responsible for 16% of the rework causes.
Figure 2-2: First level permitting rework classification causes (Fyeak et al., 2003)

In Figure 2-3, scheduling and design planning resulted in the majority (50%) of rework causes. Out of this 50%, 34% was due to incorrect design processes, 6% due to poor documentation, and 4% due to wrong review processes of drawings prior to development.

Figure 2-3: Design planning and scheduling – relative contribution (Fayek et al., 2003)

The research work conducted by Oyewobi and Ogunsemi (2010) in some selected building projects in Niger to evaluate rework states that:

- rework amounts up to 30% of construction
• potential efficiency of labour is used at only 40-60%
• no less than 10% of materials are wasted

As stated above, rework can also be created from change orders (Knocke, 1993; Love and Li, 2000). However, the level of contribution of change orders to rework and waste remains relatively unexplored. The traditional construction project management methods are not capable of successfully handling such situations to avoid time and cost overruns and wastes (Cooper, 1993). Currently, combinations of different strategies are used as there is no single appropriate project delivery system available for diverse circumstances in construction project management (Ibbs et al., 2003).

2.2 Construction project management
The construction industry is a project-based, highly fragmented and complex, one time effort. It is designed to meet customer needs with limited, budget, resources and performance specifications. Construction project management (CPM) means the overall planning, coordination, and control of a project from beginning to completion. The aim of CPM is to bring forth a functionally and financially feasible project to meet the client’s requirement (Richardson and Pugh, 1981). The management of construction coordinates many people with diverse interests, talents, and backgrounds and involves them in their interrelated roles to assure a successful project. These days, emphasis is given to the development of an integrated project management system, which involves integration of a project with the strategic plan of the organization for managing actual projects (AIA, 2009).

2.2.1 Construction environment
In any large scale construction project, construction professionals have to make decisions based on their personal experience, incomplete information, and assumptions. Thus, adjustments and changes are unavoidable. Some common features to any construction project are (Sterman, 1992):

i) multiple interdependent components with high complexity
ii) dynamic in nature
iii) multiple feedback processes and
iv) nonlinear relationships (not simple and proportional)

Project management is subjected to numerous problems of costing and scheduling. If errors made at an early stage are discovered, this necessitates costly rework and results in overtime,
schedule overrun, or reduction in quality or scope of the project. The effects of these difficulties include lower productivity, higher costs, and unacceptable levels of solid waste. This frequently results in costly litigation between owners and contractors over responsibility of overruns and delays (Sterman, 1992).

2.2.2 Project Deliveries and Construction Strategies (PDCS)

The contractual relationships chosen for bringing an owner and the tradespersons together is termed ‘project delivery’. The former wants something to be built and the latter can perform the tasks required to carry out the project construction (ADE, 2004). Publications (Pekka, 2002; Pierce et al., 2003; FHWA, 2005) can be referred for detailed description of traditional and latest delivery methods used in Canada, USA and Europe.

Project delivery can take many forms, ranging from the most traditional design-bid-build, to the newer “alternative” project delivery methods especially popular for large-scale construction projects. These range from single-firm responsibility for both design and construction, to public-private partnerships with a mix of design, build, financing, and operating responsibilities (Pierce et al., 2003). The role of design and construction providers changes with each different method of procurement and delivery, and with expectations of the owner. Importantly, the changes in roles indicate changes in the overall distribution of the risks associated with the project.

Following factors will have to be considered in determining appropriateness of project delivery system in order to satisfy the owner’s expectations (Pierce et al., 2003):

- How much input does the owner wish to have in the design of the project?
- How risk averse is the owner?
- Is determination of cost early in the project development critical?
- How is the project being financed?
- Is the completion date of the project critical?
- Are there performance guarantees critical to the Owner?

**Design-Bid-Build (D-B-B)**

The traditional delivery method in which selection of the contractor is done by evaluating the lowest total construction cost offered with separate design and construction contracts is most commonly referred to as Design-Bid-Build (Ibbs et al., 2003). In this method, separate
agreement with the design professional for design services and contractor for construction are selected by the project owner (Figure 2-4). A group of qualified contractors is selected to bid based on the completed design drawings. After the bidding process, the owner then independently contracts typically with the low bidder, to build the project.

This method does not involve the constructor into the design process. In this setting, the designer is responsible for the design quality. Risk for cost and schedule is allocated to the general contractor after the completion of the design. The responsibility for adequacy and completeness of design remains with the owner.

In this system, the owner has control over the design and construction and it is easier to get a fixed price tender from the contractor (Ibbs et al., 2003). The system is not capable of fast-tracking the construction (i.e. commencement of construction before the project design is complete) and does not have input from the contractor throughout the design phase.

**Construction Management**

The term, construction manager (CM) simply refers to the firm responsible for managing the entire construction process. The CM and design consultants are employed at the same time (Pierce et al., 2003). The CM works alongside the designers as a team member and shares construction experience with the evolution of the design (Figure 2-5).

The CM is additionally responsible for the budget and schedule of the project, during design, documentation, bidding and, construction phases. These include value engineering studies, constructability reviews, detailed budgeting, cost estimating, and scheduling.

There are typically two commonly used approaches to construction management:

(a) A “pure” Construction Manager (CM “Not-at-Risk” or CM-as-Agent)
It is significant to note that this is not a project delivery method. It is a project management method of managing (versus delivering) design and construction services. The CM is typically an agent of the owner at the stage of processing of the contract, and the owner actually enters into the various trade contracts necessary to complete the building project (Pierce et al., 2003). The owner ultimately carries the risk of the construction project, despite the fact that the CM is responsible for the scheduling and controlling of the project’s cost.

(b) Construction Manager at Risk (CM “At-Risk”)

The CM-at-Risk model is a hybrid between the traditional and the construction management project structures. It is often called “Contractor/Construction Manager Project Structure”. The CM is brought on during the design phase of the project as part of the design team. He/she needs to work with the architect (or engineer) in developing drawings (Pierce et al., 2003). At the end of the design development phase, the CM assumes the obligation to construct the project for a stipulated sum or a guaranteed maximum price.

**Design-Build (D-B)**

Design-Build is a project delivery system where the owner hires a single entity or a team for the design and construction of the project (Figure 2-6). The majority of the project risks are passed on to the Design-Builder (usually the general contractor), who is obligated to produce a completed development to the owner (Alaska Department of education, 2004; Pierce et al., 2003). The advantage of D-B over D-B-B is involvement of the contractor during the whole project life cycle. The owner has literally no legal responsibility for the project until the building is completed and title is transferred to the owner. The lack of representation of a design professional from the owner is the major disadvantage of this system.
**Partnering**

The best features of the traditional D-B-B and the D-B methods are used in this delivery method (Figure 2-7). Both the architect and contractor are under direct contract to the owner. Both the contractor and the architect are hired and selected at the same time (Pierce et al., 2003). The owner gets an architect of his choice. The architect may work in support of the owner and perform unbiased contract administration. The contractor is allowed from the beginning to organize budget, schedule, and methods of constructability. A check and balance of program, design, and budget is maintained among the owner, architect, and contractor.

![Figure 2-6: Design-Build](image)

**2.2.2.1 Public construction procurement**

The literature review indicated that there is no significantly new project delivery method used for public construction procurements (Table 2-2). Almost all the delivery methods are mere modifications or slight variations of existing or past methods. The most widely used delivery method is the traditional method of D-B-B (FHWA, 2005). Two recommended forms of contract in D-B-B for publicly funded projects are the Stipulated Sum Contract and the unit price contract (PCCBC, 1998). SSC is the most widely used and recommended type of contract for most public construction projects.
### Table 2-2: Distribution of project delivery methods

<table>
<thead>
<tr>
<th>DELIVERY TYPE</th>
<th>2004</th>
<th>2007</th>
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</thead>
<tbody>
<tr>
<td>Design-bid-build</td>
<td>95-98%</td>
<td>92-95%</td>
</tr>
<tr>
<td>Design-build</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Performance-based</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Concessions</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>PPP/DBMF</td>
<td>2-5%</td>
<td>2-5%</td>
</tr>
</tbody>
</table>

(Adopted from FHWA, 2005)

The general contractor quotes the stipulated sum to complete the work which becomes the cost of work. This cost is affected by changes to the scope of work. The second most common form of contract is Unit Price Contract (UPC), used for engineering projects such as buildings, roads, bridges, and dams. In UPC, the work is divided into a sequence of units. Each unit describes the work, estimated quantity, and its price. The contractor quotes a unit rate for each of the different units or categories. The total price for each item is obtained by multiplying calculated quantity by the unit rate of that item. Other forms of contracts are used in special circumstances. D-B seems to be increasing in use as a viable delivery method (PCCBC, 1998), and it has many advantages compared to the traditional method (D-B-B). Traditionally, the public-private partnership (PPP) contractual model has been considered and used by the government public sector to achieve better “value for money” for taxpayers.

**Design-Build-Operate (D-B-O)**

Under this project delivery method, there is an obligation on the part of the organization in designing, building, and operating the project’s asset/service. It is frequently used in the privatization of public projects. A single end responsibility for design and construction is created by simple D-B approach. It facilitates the fast completion of a project by overlapping of the design and construction phases of the project (Pierce et al., 2003). However, combining all three processes in a D-B-O approach maintains the required involvement of private sector. The user fee generated during the project phase also facilitates private-sector financing of public projects.

**Design-Build-Finance-Operate (D-B-F-O)**

If financing is added to the project, it is secured by either the public entity or the private-sector company. In the former case, it becomes a D-B-O with public financing, whereas the latter becomes a D-B-F-O. No matter how the project is financed, the public entity retains ownership and ultimate control (Pierce et al., 2003). Once completed, the D-B-O or D-B-F-O
contractor guarantees performance and assumes the responsibilities of operations and maintenance.

**The Benefits of Public Private Partnership**

The benefits D-B-Os offered to public-sector owners are lower costs, faster schedules and fewer risks. In D-B-Os, control of the facility remains under the control of the owner while D-B-O partner is responsible for performance and compliance. The risk and liability can be managed by both the owner and the D-B-O partner through performance guarantees and insurance (Pierce et al., 2003). The development of maximum total project cost is guaranteed in the beginning and it ensures implementation of quality assurance and control processes. Therefore, D-B-O partner now serves as the single point of contact and management of the project by the owner becomes easier.

If design, construction, and operation are handled together from the outset, there are more opportunities for efficiency. Cost savings continue until the construction phase is complete or even after completion of construction. Moreover, decisions made during the planning process continue to gather rewards during operation (Pierce et al., 2003). The project timeframe can be shorter because many aspects of project planning, design, construction, and procurement are done at the same time by the same team. All team members are involved from the start, with no “down time”. It is to be mentioned that down-time is generally associated with the transition of a project from one phase to the next in a more traditional D-B-B arrangement.

**2.2.2.2 Integrated Project Delivery (IPD)**

Since complexity of the buildings is increasing day by day, a new project delivery method is introduced to improve the cost, schedule, and quality of projects over traditional delivery methods referred to as Integrated Project Delivery (IPD) (AIA, 2009). The AIA defines IPD as:

“a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harness the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication and construction.” (AIA, 2009)
The common principles used to define IPD are:

i) Multi-Party Agreement: The primary goal of IPD is to maximize collaboration and coordination throughout the project. When IPD is used, typically the owner, architect, general contractor, and any other party who may have a primary role in the project enter into a single contract for the entirety of the project.

ii) Risk and Reward are shared: IPD contracts combine the risks and rewards of all team members and incentivize collaboration in order to reach common project goals.

iii) Early Involvement of All Parties: One of the most fundamental advantages of IPD is the ability to involve all parties in a project from the earliest design phase.

While this early collaboration does not require the use of technological tools, it is important to note that information technology, such as BIM, can greatly enhance the efficiency of collaboration across all phases of a project (AIA, 2012). However, at present, the public sector is not ready to accept BIM at the level of IPD (Succar et al., 2009). The use of BIM is not necessarily required as a tool to adopt IPD practices. However, BIM forces the management system to think of changing the current process (Franklin et al. 2010).

2.2.3 Change management

Project performance and delivery is controlled by certain variables. These variables have been traditionally listed as scope, cost, and time and represent a ‘project management triangle’ where each side represents a variable. When one side of the triangle (value of any variable) is changed, other two sides are affected (Figure 2-8). The most important among these is the scope, which is considered one of the major responsible factors to create uncertainty in the construction. (Lee et al., 2003a). The impact of change could propagate costly consequences, which would delay and disrupt the entire organization if not identified promptly. Design changes occurring during construction are considered the most substantial sources resulting in construction and demolition (C&D) waste (Osmani et al., 2008). Change management aims to forecast possible ripple effects, plan preventive impacts, and coordinate changes across the entire project.
A change that takes place during a project can be incremental or sudden. Incremental change is gradual and happens over a prolonged period of time with low effects. Sudden changes occur more often in post-design phases (Lee et al., 2003a). Causes of project change may originate mainly from either external or internal sources. External causes may be due to changes in the customer expectations and needs or economy, while changes in management policy or the organizational objectives may be the internal causes.

If not managed properly, most of the changes can result in cost and time overruns along with generation of unacceptable amount of solid wastes (Osmani et al., 2008). Direct and indirect effects of changes in the project would ultimately have an impact on project cost and schedule. Addition or deletion of work, demolition, rework, time loss, revisions of designs and schedule are some of the direct effects. On the other hand, multiple interdependencies among the activities create indirect effects on productivity, coordination, procurement, and schedules (Love et al., 2011).

2.2.3.1 Traditional change management approach

A generic change management process model is defined based on case studies and review of existing research (Figure 2-9). The model consists of four stages: Identify, Evaluate, Approve, and Implement (Hao et al., 2008).
Identify
During construction, the project team actively seeks to identify potential changes at the earliest opportunity or changes due to owner needs and expectations (Hao et al., 2008). This is achieved through the review of 2D design/drawings created at the start of the construction process. Once the change is identified, designs are modified and tentatively marked on the 2D drawing for evaluation. At this stage, detailed designs are not prepared. Schedule and cost analysis is also not performed due to non-availability of change in the items of work.

Evaluate
Evaluation steps include implication assessments and optimum selection of change options based on past experience and historical project data available at site (Hao et al., 2008). Once the evaluation step is complete, its impacts on the project performance are analyzed by the appropriate member of the team (for example: project manager).

Approve
The change is then finally approved by the owner in consultation with the project management team. There can be several iterations during the approval process. It is important to note that revised cost and proposed schedule estimates are based on tentative designs and the experience of the team (Hao et al., 2008).
Implement

Once a change is approved, it is communicated to all team members, whose work is affected by the change. Detailed revisions of design/drawings are performed by the design team and schedule of work is adjusted with projected cost (Hao et al., 2008).

2.2.4 Cost estimating and management practices

Cost Management is utilized as an approach of balancing a project's performance and scope throughout the planning, design, and development phases. For complex or sizeable projects, five categories of estimates are prepared (PWGSC, 2012). The process begins with the development of an initial estimate, which is further developed during the early phases of the project. Pre-tender estimates (Class ‘A’) are prepared in elemental cost analysis format based on completed construction drawings and specifications prepared prior to calling competitive tenders. The Class 'A' estimate is generally expected to be within 5% to 10% of actual contract award price for new construction. Specifications-writing is followed in standard ‘MasterFormat’ (CSI, 2013) for most commercial building design and construction projects in North America to facilitate communication among architects, engineers, contractors, and suppliers.

During construction, management focuses on the responsive cost management for any changes in the work. These are the value engineering change proposals, sometimes proposed by one of the parties for a better-value substitution (WBDG, 2010). A detailed cost review is performed for the additional quantities of ‘items of work’ based on the revised designs to be presented to the general contractor, who needs to agree before the work is installed. The cost data captured for this purpose is based on current unit-price of each ‘item of work’. Unit price cost estimates are based on quantity takeoffs from detailed design documents. They are developed by adding up the direct costs of materials and supplies, labour, and construction equipment for each individual task (RCD, 2013). Overhead and profit at a subcontractor level are added to these direct costs, which gives the in-place construction cost per unit of work required.

RSMeans (RCD, 2013) is a construction estimation database that is used by professional estimators for up to date labour, materials, and overhead costs for specific project types and locations (Figure 2-10). The RSMeans data is an estimation source that helps to calculate the costs of construction prior to start. The database is used for a wide variety of construction types and the estimate is based on overall materials, square footage, and location. It can be
used at almost any stage of cost planning, but it would become more accurate during the progress of the project with the availability of current market rates.

![Figure 2-10: Construction estimation database (RCD, 2013)](image)

### 2.2.5 Earned Value Management

Earned Value Management (EVM) methodology is defined as a management technique of associating resource plans and its usage by the way of proper scheduling and performance management (Kim et. al., 2003). Earned Value Analysis (EVA) integrates cost, schedule and scope. It can be a useful tool to forecast project completion dates and future performance of a project (Figure 2-11). Problems can be identified and controlled before they become intractable with EVM as a project management tool. It helps in managing the project within the stipulated budget and time.

![Figure 2-11: EVA Graphical Representation](image)
Cost performance measurement using Earned Value Management consists of three basic quantities (Javier et. al., 2011). These are Budgeted Cost of Work Scheduled (BCWS) or Planned Value (PV), Budgeted Cost of Work Performed (BCWP) or Earned Value (EV), and Actual Cost of Work Performed (ACWP) or Actual Cost (AC). These terms are defined below:

- Planned Value (PV) or Budgeted Cost of Work Scheduled (BCWS) is the total value for all the items of work scheduled to be accomplished within a stipulated time period.
- Earned Value (EV) or Budgeted Cost of Work Performed (BCWP) is the total budgeted value for all completed work and work under construction within the time period under consideration.
- Actual Cost (AC) or Actual Cost of Work Performed (ACWP) is the real cost invested in completing the work within a stipulated time period. The value for ACWP is only accounted for the work executed to date against the value for which a BCWP is completed.

Table 2-3 shows the summary of important EV terms and relations:

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>Cost Variance (CV = EV – AC)</td>
</tr>
<tr>
<td>SV</td>
<td>Schedule Variance (SV = EV – PV)</td>
</tr>
<tr>
<td>CPI</td>
<td>Cost Performance Index (CPI = EV/AC)</td>
</tr>
<tr>
<td>SPI</td>
<td>Schedule Performance Index (SPI = EV/PV)</td>
</tr>
<tr>
<td>BAC</td>
<td>Budget At Completion (planned cost of project)</td>
</tr>
<tr>
<td>PMB</td>
<td>Performance Measurement Baseline (the cumulative PV over time)</td>
</tr>
<tr>
<td>IEAC</td>
<td>Independent Estimate At Completion (the forecasted final cost)</td>
</tr>
<tr>
<td>ETC</td>
<td>Estimate To Complete</td>
</tr>
</tbody>
</table>

(Adapted from Lipke et al., 2009)

It seems that EVM has not been widely adopted by the private sector (Kim et al., 2003) but due to the increasing global competition and rapid technological developments, industry is forced to adopt new management methods to improve control of their projects.

EVM is perceived as being a good forecasting tool because of its important utilities of predicting the time of completion and the total cost of the project at completion. It is capable of identifying the impacts of cost and schedule overruns because of known problems. It enables project managers to better analyse the problems and plan projects in advance (Kim et al, 2003). High acceptance of EVM in public and private sectors suggests its usefulness in small projects also (BIM smart market report, 2009).
2.2.6 Earned Schedule (ES) concept

The lifecycle plot of a construction project is typically an ‘S’ shaped curve and needs the maximum efforts during the middle of its lifecycle. All planned activities will be nearing completion during the period when the project is close to its end. During this period, budgeted cost of scheduled work tends to be equal to the planned cost of work performed. A project’s earned value will be inclined to its planned value. Consequently, SV will converge to a value zero and SPI will incline to a value equal to one. This situation can be reflected even in case of serious delays from the planned schedule. Thus, EV management is not capable of predicting the relevant cost and time information during final stages of the project. Lipke et al., (2009) proposed the use of Earned Schedule (ES) to overcome this limitation. ES indicates the date of completion of the work which should have been achieved for the current value of work completed. To compute ES (Figure 2-12), earned value is first calculated at time ($t_{AT}$). The date when EV would be equal to PV is then computed by projecting this EV at time $t_{AT}$ on the PV line (the cost base line). This date is the Earned Schedule (ES).

![Figure 2-12: Earned schedule graphical representation](image)

Any partial value of time can be calculated by linear interpolation. At present, final duration for the schedule component of projects is not supported by EVM application guidance. Table 2-4 shows the terms and relations used in ES.
Table 2-4: Terminology Used in Earned Schedule Management

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>Actual time (Number of time increments corresponding to EV)</td>
</tr>
<tr>
<td>ES</td>
<td>Earned Schedule</td>
</tr>
<tr>
<td>PD</td>
<td>Planned Duration</td>
</tr>
<tr>
<td>SV(t)</td>
<td>Schedule variance (time); ( SV(t) = ES - AT )</td>
</tr>
<tr>
<td>SPI(t)</td>
<td>Schedule Performance Index (time); ( SPI(t) = ES/AT )</td>
</tr>
<tr>
<td>IEAC(t)</td>
<td>Independent Estimate at Completion (time)</td>
</tr>
</tbody>
</table>

(Adapted from Lipke et al., 2009)

It is discussed in the section 2.2.6 that final cost could be forecast from the relation \( IEAC = BAC/CPI \). In a similar manner, final duration could be predicted from the relation:

\[
IEAC(t) = PD/SPI(t)
\]

Where, PD is the planned duration for the project and \( IEAC(t) \) is the independent estimate at completion (time).

Information about the scheduled time indication makes it possible to compare the scheduled time of the project in accordance with the PMB. The duration at which the EV accrued is recorded is denoted by actual time \( t_{AT} \) (Lipke et al., 2009). The formulation of time-based indicators is done from the values of ES and AT. Schedule variance is termed as \( SV(t) = ES - AT \), and schedule performance index is calculated using relation \( SPI(t) = ES/AT \).

A greatly simplified method of forecasting the final duration and completion date is offered by Earned Value management system with reliable results. Henderson et al. (2006) performed a study to compare ES to critical path prediction and confirmed that ES management is capable of better predicting project performance that EV management.

2.2.7 Need of improvements in construction procurement

The current condition of the construction industry needs to be understood to formulate specific goals for improvements. Dissatisfaction with traditional contractual forms has led to the development of alternative delivery methods. Most of these variations merely represent the shifting of the risk from one team member to another (FHWA, 2008). This section addresses the weaknesses in the currently popular delivery systems, and points to a more efficient way of building (Ibbs et al. (2003); Pierce et al., 2003).

- The basic problem in the designing and construction of building projects is the incorrect visualization of the project information. It is critical that the designers and owner/end users understand one another in relation to the project requirements.
• The complexity of construction projects is the involvement of so many individuals and this creates strenuous demands on the communication between the project team members. Most design and construction related activities of conveying information consists of ideas transformed between the 2D representations and the 3D space (AIA, 2009).

• Construction teams often do not behave as one team challenging the project, but as competing teams challenging one another.

• Lack of sufficient collaboration and information among the project team member leads to costly litigations.

The planning and designing process itself needs to be analyzed through improved process of all the planning related activities. It is possible to improve the preconstruction process through better collaboration and faster coordinated turnaround time between project team members. BIM is a relatively new computer technology through which building performance is simulated digitally to resolve design conflicts during the pre-construction stage and avoid costly abortive work at the construction stage (BCA, 2011).

2.3 Building Information Modeling (BIM)

NBS (2012) states that, “The building information model is a project as well as a process simulation. It is a digital representation of physical and functional characteristics of a facility. The planning and realization of BIM are very similar to the planning and realization of the actual construction project” (NBS, 2012). The simulation process actually parallels the construction process, which makes BIM such an effective tool. Development of BIM is through the shared knowledge of AEC team which makes it a reliable resource for information about a facility. This is the reason why BIM proves to be a reliable basis for decisions during a project’s life-cycle, from concept initialization to its demolition (NBS, 2012).

In recent years, BIM has received enormous interest due to its impact on sustainable development and its ability to integrate information and optimization of processes. BIM helps to achieve levels of coordination far in excess of the current norms (Schlueter et al., 2009). The traditional, document-based, 2D computer aided design (CAD) planning environment does not support this integrated view of the building (Howard and Björk, 2008). A building information model is a richer repository of information than a set of 3D information. It is capable of storing objects, spaces and facility characteristics in a digital database (Eastman,
It has the ability to parametrically capture design intent, which reduces the likelihood of coordination error. It can rapidly perform iterative changes, too (Fu et al., 2006). Cost data can be associated with each element to obtain in a detailed cost schedule (Popov et al., 2010). BIM objects can also be linked to a various sources of information through hyperlinks. This hyperlinked model can function as a Graphical Information System (GIS) for the building (Isikdag et al., 2008; Li and Cheng, 2005). Process simulation creates a virtual feedback loop such that challenges related to design, construction coordination, and sequence can be identified prior to commitment of field process. The simulation process of BIM increases predictability in the project delivery process by integrating project data. Therefore, it gives a global and synoptic view of the project (Popov et al., 2010). They described BIM as the tool capable of working together with discipline-specific solutions. All information about the facility and its lifecycle; defining and simulating the building; information related to Heating, Ventilation, Air Conditioning (HVAC), structure, electrical and plumbing, mechanical and design, and planning and management are included.

### 2.3.1 Construction management and BIM

Conventional delivery methods often lead to a division between build team members, since work is handed off from one member to the next throughout the process. The greatest amount of efforts is focused during the construction documentation phase in a traditional project delivery system. By this time much of the design has already been developed. At a later stage of the project, cost and schedule inputs by the construction team can lead to significant design changes (Figure 2-13).

![Figure 2-13: Early decision making (buildingSMARTalliances, 2010)](image-url)
The BIM workflow provides a more collaborative method for integrated design early in the design stage, which emphasizes the development of a holistic design (Popov et al., 2010). All the members of a project work together in a coordinated way from the beginning of a project until completion. This possibility makes BIM an inherent part of an Integrated Project Delivery method (AIA, 2009).

### 2.3.2 Modeling concept

3D solid modeling of Buildings was first developed in late 1970s and early 1980s (Eastman et al., 2008). This work was carried out in parallel with the efforts to develop mechanical, aerospace, building, and electrical product design.

**Object based parametric modeling**

The evolution of current generation of BIM design tools is derived from the object-based parametric modeling capabilities, which were developed for mechanical system design (Eastman et al., 2008; Marian, 2009). Parametric information refers to the information about an object of similar family that distinguishes one particular component from another similar one (Grilo et al., 2010). For example, this may refer to a wall. All walls have wall qualities in common, but each actual wall, although made with the same “wall tool,” may have different parameters, dimensions, material makeup (wood or metal studs, type of sheetrock, etc.), supplier information, etc.,. The shape instances and other properties are defined and controlled in accordance with the hierarchy of parameters. The shapes can be 2D or 3D.

In traditional 3D CAD, every aspect of an element’s geometry has to be edited manually. A parametric modeller automatically adjusts to the changes in context. Conceptually, “BIM tools are object-based parametric models with a predefined set of object families [e.g., wall, floor, door, window and so forth] each having behaviors programmed within them” (Eastman et al., 2008). A building is an assembly of objects defined within a BIM system. The identical parts and parts that belong to a product family with common information contained in a building are stored in a ‘standard part library’.

The *OmniClass* Construction Classification System (OCCS) is a strategy for classifying the entire built environment. It is designed to organize library materials. It also provides a standardized basis for classifying and retrieving information as well deriving relational BIM applications (OmniClass, 2013). This helps in the design analysis process by increasing interoperability among the BIM software.
2.3.2.1 Model development through feedback loop

A fundamental characteristic of BIM is its ability to be developed via an information feedback loop. The development of the model and the relevant project information are performed in an iterative manner. Since the different project team members work on the project model, the available information gradually increases in scope, depth, and relatedness. A coordinated and intelligent model evolves with the building information being cycled continuously through the BIM at greater detailing and coordinated level (Eastman et al., 2008).

The circle represents milestones in the process, where a project passes through critical stages. Moreover, evaluation and reflection can take place in the model (Figure 2-14). The spheres in Figure 2-14 indicate the way of collecting information and development of the project, since more information is connected to the project over time. The arrow represents time and the flow of information over time.

2.3.2.2 Virtual construction simulation

Building information modeling simulates the construction project in a virtual environment (Figure 2-15). Virtual building makes it possible to practice construction, to experiment, and to perform adjustments in the project before it is materialised through the use of a software package (Eastman et al. 2008; Grilo et al., 2010). Most relevant aspects of the project can be communicated and considered before finalizing the construction documentation through virtual and planning and building.
2.3.2.3 Model intelligence

Model intelligence refers to the property of storing information of objects in a 3D virtual model. This information includes the dimensions (size), the quantity of objects, the relative location of the object, and other parametric information about the object in the model (Eastman et al., 2008). This information can be retrieved and used for further analysis, making it an intelligent model. Models of different disciplines of a project can be linked to make an integrated model with all the sub-models information embedded in it. This allows for another dimension to model intelligence.

2.3.2.4 Linking

Linking is an important concept in virtual construction simulations and it refers to the interlinking of different sources of information into a single 3D model. Even this information could be stored in a separate file such as in a text document, a database or a spreadsheet. Parametric objects in the model are linked to their own information in a schedule format (Eastman et al., 2008). It is possible to change the parametric values for these elements by changing the values in the schedule.

Another common link in BIM exists in the interoperability of various models created by different software tools. This implies that it is necessary for a model to be friendly with models created by other software tools. Hence, the entire object’s information can be transferred correctly from software to software without any loss of information.

2.3.3 The BIM Applications

The literature review indicated that BIM applications were limited up to the preconstruction phase, with a limited amount of research regarding its application and related data collection during construction process. Goedert et al. (2008) described the applications of BIM
throughout the construction phase of the project life cycle. Research was conducted simultaneously with traditional methods on military base underground services to determine the feasibility of representing the construction process and related documents in a similar format. 3D as-built data was captured into the BIM model with a custom built laser range finder system and their corresponding x, y and z coordinates were collected and stored in MS Excel and Revit. Documentation of the actual construction schedule as per the daily progress site report was then created using MS Projects and Revit API.

Popov et al. (2010) worked on the methods to determine the most effective alternative of the project using theoretical principles along with practical applications of BIM and construction process simulation techniques (Figure 2-16). The application programs covering virtually each phase of the specific construction development (e.g. planning, designing, cost estimation, fabrication, and construction) were developed. These programs were used to solve the problem associated with the underestimated demand for resources while selecting the most efficient investment in construction. These were also supplemented with the resource demand calculation and comparing the alternatives. The 5D concepts described in this article contain 3D BIM as the core component with the inclusion of time related and cost related data as two other dimensions, respectively.

![Figure 2-16: 5D concept of the construction process (Popov et al., 2010)](image)

Popov et al. concluded that

- BIM can effectively manage both graphical views and information
- Information sharing is created and facilitated through BIM
- BIM can be used as an effective tool for Virtual Project Development in the
construction industry and 3D model can be used for simulating the construction.

Lee et al. (2003) proposed a BIM model (Figure 2-16) that could support the project financial decision making process by providing real-time cost information based on the planned and changed interior design. Validation of the model was carried out with a case study analysis for the interior design of a housing project involving 1000 apartment units, each of 100 m².

Stumpf et al. (2009) utilized a BIM based modeling technology in energy simulations at the early design process. The project team utilized a prototype BIM model in energy simulations and compared results during the conceptual design phase (Figure 2-17).

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Two separate buildings</td>
<td>Two-story building</td>
<td>One-story building</td>
</tr>
<tr>
<td>Plan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3D-CAD</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2-17: Comparison of different energy estimations (Stumpf et al., 2009)](image)

Several other real time BIM based approaches have been used in construction management (Aron et al., 2008; Nepal et al., 2009; Popov et al., 2009). However, no literature evidence is available in the construction waste management area to the best of the author’s knowledge.

2.3.4 Quantity takeoff

Quantity takeoff is essentially the process of quantifying the material needed to complete the work specified for a project. The measurements are typically taken from the paper manually with the help of a red pen and a clicker or a digitizer.

2.3.4.1 Traditional Estimating Versus BIM-based Estimating

Estimation process typically begins by importing their CAD drawings into a cost estimating...
package by digitizing the architect’s paper drawings. They may also do manual takeoffs from their drawings. All of these methods have possible human error associated with them and may result in incorrect data accusation from the original drawings.

The first step of cost estimation is quantification. The digital computable information attached to 3D objects of a building information model makes quantification effortless. BIM can generate the takeoffs, counts, and measurements directly instead of taking them manually from drawings. Figure 2-18 shows all the above information as calculated from the model used by Autodesk 2010. Therefore, the information retrieved is always coherent with the design. All related construction documentation and schedules; including takeoffs, counts, and measurements are automatically updated if any changes are made to the design.

![Figure 2-18: Snapshot of quantity takeoff (Autodesk, 2010)](image)

With BIM, the quantity takeoff can be greatly sped up because the model has the information about all the objects in the building as well as their dimensions. Regardless of the phase during a project from design through construction, BIM generates rapid material quantity takeoffs and performs estimates. BIM automatically measures area and counts building
components such as walls, doors, and windows. Finally, it produces reports. Because of requirement of cost related data BIM solutions can’t generate automatic cost estimates however, it has significant advantages of minimizing manual takeoffs over traditional drawing-based systems.

2.3.5 Interoperability

Interoperability is the ability to handle and communicate the project data among collaborating firms working on different platforms. BIM is widely accepted as the preferred method of communicating and collaborating among the AEC. These data-rich models can be used by other members of the design team to coordinate the various systems in the building, including structural, electrical, and mechanical. The free exchange of data across different applications and platforms allows for better integration of the project delivery (buildingSMARTAlliance, 2011). The construction industry has the most fragmented supply chain of the AEC industry and BIM platforms may not be interoperable. The three most common ways to achieve interoperability between various software applications are:

- Software applications developed that directly reads the information contained in another BIM software application.
- Using BIM software that provides an Application Programming Interface (API), to facilitate development of interface between software from different providers.
- Using BIM software that facilitates data exchange standards which has industry-wide acceptance.

2.3.6 Current Status of BIM in the Construction Industry

Studies on BIM are limited in spite of its importance as an emerging research field. Therefore, some of the information related to BIM is available in the form of white papers and technical reports (i.e. IBC, Cefrio, Allen), guidelines and reports generated by government and other regulatory bodies (i.e. FHWA, CRC, BSI, COBIM), and articles in well-respected online newsletters (i.e. aecbytes, buildingSMART). These studies have explored the current status of BIM adoption, usage, costs, and benefits.

2.3.6.1 BIM adoption

Adoption of a new technology in any industry poses challenges. McGraw Hill Report (2009) on BIM adoption in the United States shows that almost 39% of the construction industry is now using BIM in major projects with separate design and construction procurement
processes.

The Institute for BIM in Canada (IBC, 2012) has undertaken a survey focused on BIM, with the purpose of better understanding the issues related to use and adoption of BIM in the Canadian construction industry in 2011. It highlights the gaps in the existing practices and identifies that procurement is still organized around functions and projects, not around processes. Further, it mentions the lack of recognition by public clients on the added value of BIM technology.

In November 2011, National Building Specifications in UK (NBS, 2012) followed up their 2010 BIM research with a further survey to track people's attitudes towards its use. The survey revealed that around 90% of users adopting the BIM process required a significant adjustment to the current practices in the industry. A few larger architectural organizations have been asked to use BIM in bidding for public projects (NBS, 2012). It is realized that while cost is often seen as the barrier to entry, especially for small organizations, the real challenge appears to be the process/practice.

A survey conducted by buildingSMART (2010) Australia and the School of Natural and Built Environment (University of South Australia) has provided a useful illustration of the current status of adoption, usage, costs, and benefits of BIM in Australia (Allen Consulting Group, 2010). Nevertheless, BIM requires a shift in the existing technology, as well in the approach of design and construction teams work (Staub-French et al., 2011). According to the Cooperative Research Centre for Construction Innovations in Australia (CRC, 2008), there are many technological barriers to implementation of BIM. This can be related to the needed organizational changes and changes to the business processes.

Even though BIM is expected to deliver many benefits, the overall costs are not higher than traditional or alternative management approaches. However, there are many factors impeding widespread adoption. The Canadian construction industry has identified bottlenecks in the adoption process (Cefrio, 2012) and arrived at the conclusion that interest in BIM is high. However full scale BIM projects are rare.

2.3.6.2 Data exchange standards

One of the most dominant factors in widespread use of BIM is the reluctance from public sector organizations to using proprietary software or standards. To keep the information open and non-proprietary, there is a need for standards and protocols with a common language.
This would enable the software packages to communicate with each other. At present, there are various existing protocols to address interoperability issues. The IFC and the Standard for the Exchange of Product model data (STEP-ISO) are first to introduce such protocols (BuildSMART, 2013). At present, the IFC is the most supported protocol among the major BIM software vendors.

IFC standardization is considerably more open than past CAD efforts. It has been proven to be more anticipatory than previously used CAD standards in already existing technological solutions. The IFC 2×3 platform has been in use for over five years. All the major software vendors have solidified their 2×3 interfaces, making it the most robust BIM model exchange platform available today (AECbytes, 2012). In the year 2006, the IAI consortium was rebranded to buildingSMART with a new vision to emphasize interoperability means for users and businesses. Public sector property owners around the world have been the most influential supporters of IFC-based interoperability in connection to issuing requirements and guidelines for the increased use of BIM technology (Laakso et al., 2012).

### 2.3.6.3 Critical factors for BIM implementation

In a study conducted by Love et al. (1999) it was concluded that individuals and organizations involved in the procurement of building and engineering facilities suffers from major behavioral, cultural, and organizational differences due to the traditional separation of design and construction processes of the construction industry. To achieve efficient project delivery, owners need to bring the procurement team together early in the project (Staub-French et al., 2007). Those projects, that are procured using traditional lump-sum contracts with lack of coordination experience higher levels of rework than alternative methods (Love et al., 1998; CIDA, 1994).

### 2.3.6.4 BIM maturity levels

Though BIM continues to develop, not all businesses would adopt systems and technologies at the same rate. BIM adopters will need to go through a managed process of change, which encompasses their internal organizational interfaces with external supply-base and clients. A maturity model shown in Figure 2-19 was developed by the UK Department of Business Innovations and Skills (BIS, 2012). BIS defined the levels from 0 through 3. A majority of the market is still working with Level 1 processes. However, the best in class are experiencing significant benefits in Level 2.
Model Progression Specifications (MPS) for BIM (E202-2008) have been adopted by the American Institute of Architects (AIA, 2012) to address:

a) Phase outcomes, milestones, and deliverables

b) Idea of assigning tasks on a best person basis (American Institute of Architects, 2012)

The core of the MPS is the Level of Detail (LOD) definitions (Table 2-5), which describe the steps of the BIM element logical progress. The LOD ranges from the lowest level (100) of conceptual approximation to the highest level of representational precision (500).

![Figure 2-19: BIM maturity levels UK (BIS, 2012)](image)

Table 2-5: Model Progression Specifications (AIA)

<table>
<thead>
<tr>
<th>Level of detail</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Content</td>
<td>Conceptual</td>
<td>Approximate geometry</td>
<td>Precise geometry</td>
<td>Fabrication</td>
<td>As-built</td>
</tr>
<tr>
<td>Design &amp; Coordination (function / form / behavior)</td>
<td>Non-geometric data or line work, areas, volumes, zones etc.</td>
<td>Generic elements shown in three dimensions</td>
<td>Specific elements Confirmed 3D Object geometry</td>
<td>Shop drawing / fabrication</td>
<td>As-built Actual</td>
</tr>
<tr>
<td></td>
<td>maximum size, purpose</td>
<td>dimension, capacities, connections</td>
<td>purchase, manufacture, install, specified</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(A portion of table adopted from American Institute of Architects, AIA-E202 element model table)

2.3.6.5 Model definitions

One of the biggest concerns with using BIM for public clients, contractors, and others, is the fear that the legal framework is too unsettled (BIM SmartMarket Report, 2009). ConsensusDOCS (2010) has issued a document (Richard et al. 2010) on the BIM. It is called “ConsensusDOCS 301 BIM Addendum”. It addresses the specific rights and obligations, with a goal of enabling stakeholders to easily and effectively introduce the BIM process into construction projects. The BIM addendum is intended to be an extremely flexible document.
and used with traditional project delivery methods such as D-B-B. The BIM Addendum can be used as three-dimensional computer models coexisting with traditional two-dimensional drawings. From the design and construction standpoint, the BIM Addendum makes a distinction between two principal types of models: Design Model and Construction Model. All of the Design Models are intended to be coordinated together to form a Full Design Model (Richard et al. 2010). The construction Model consists of data imported from the design model, and it is defined as equivalent to shop drawings. The BIM Addendum defines the Federated Model as:

“a model consisting of linked but distinct component models, drawings derived from the models, texts, and other data sources that do not lose their identity or integrity by being linked, so that a change to one component model in a federated model does not create a change in another component model in that Federated Model.” (ConcensusDocs, 2009)

A conceptual diagram prepared by the authors to explain different models is shown in Figure 2-20 (Richard et al., 2010).

Figure 2-20: Diagrammatic representation of model definitions (Porwal et al., 2013)

2.3.7 Legal and contractual issues
The use of BIM in a project raises important contractual issues relating to project responsibilities and risks, contractual indemnities, copyright, and use of documents not
addressed by the standard industrial contract forms. This is a potential major concern of speedy adoption of BIM. To address specific concerns raised by BIM, the American Institute of Architects (AIA, 2009) has released its ‘Building Information Modeling Protocol Exhibit’, which is intended to be attached to owner–architect and owner–contractor agreements. An alternative family of construction industry contracts is the ‘ConsensusDocs’, that covers a wide range of digital communications, ranging from drawings to emails to payments, and specifically focuses on the BIM models (Richard and Jason, 2010).

2.3.7.1 Risk allocations
The main risk with BIM is its unsettled legal framework. The very nature of BIM introduces additional risks that must be allocated among the project participants. One of the risks unique to a BIM based project is that the project participants may assume contributions of another project participant as accurate. To account for such risks, the BIM Addendum has specified that each party is responsible for any contribution made by them (Richard and Jason, 2010). In addition, each party agrees to waive claims against the other parties over the Governing Contract for consequential damages arising out of, or relating to the use of, or access to, a BIM Model. The BIM Addendum also addresses another unique risk associated with the threat of a software malfunction, which is to be borne by the owner.

2.3.7.2 Intellectual property issues
Compared to two-dimensional drawings and specifications, the BIM Models contain a tremendous amount of electronic information that can be transmitted quickly and efficiently, and can be easily extracted and reused in whole or in part. In particular, the final BIM Model may have a significant value for the owners. It can be used to enhance management of facilities over the entire project lifecycle. The BIM Addendum specifies that the owner's entitlement to use the Full Design Model after completion of the project is governed by the contract between the owner and the design professional (Richard and Jason, 2010). Further, each party grants other party a limited, non-exclusive license to reproduce, distribute, display, or otherwise use that party's contributions for the needs of the project.

Specific modifications are likely to be required for a specific project. It appears that either of the forms of ‘AIA's E202 BIM Protocol Exhibit’ (AIA, 2012) or ‘ConsensusDocs 301 BIM addendum’ (Richard and Jason, 2010) could provide an appropriate starting point for an exhibit to be attached to the owner–architect agreement.
The management of construction is complex and its environments are dynamic and unstable. There are significant and unpredictable effects on the organization and management due to the changes during the project’s development. Thus, changes can only be managed effectively if their effects and behavior are properly understood by the project managers and appropriate actions taken accordingly.

2.4 System Dynamic Modeling (SDM)
System Dynamics, originated by Forrester (1958), is a system analysis approach. It is concerned with the study of dynamics by representation of real world systems through creation of models. It is the methodology used to understand variations in behavior between component variables over time by imitation of the system through numerical calculations performed by a computer on the model. Real life does not allow one to analyse the things by going back in time and change the way things are. However, simulation gives power to change a system virtually and analyze it in different conditions. Although there is wide application of system dynamics in different fields of business management, one of the most relevant areas for application is project management (James and David, 2008).

2.4.1 The simulation approach
System dynamics is an academic discipline and originally rooted in the management and engineering sciences. In the field of system dynamics, a system is represented by collection of continually interacting elements over time united into a whole. These components with defined relationships and connections within a system are called the structure of the system (e.g., an ecosystem).

The term “dynamics” refers to constant change over time. In a dynamic system, the variables interact with each other to stimulate changes over time. System dynamics methodology enables to understand the way systems change over time. “The way in which the elements or variables composing a system vary over time is referred to as the behavior of the system”, (Forrester et al., 1992). As a first step, a system dynamics model is constructed with all the relevant initial conditions specified. The model is then simulated to understand the behavior of system over time. The observation of quantitative interaction of variables within a system can be easily understood through graphical interface of a computer simulation program.

2.4.2 Stock, flow, convertor and connector
Any complex system can be described and analysed through graphical interface made up of
four building blocks, as shown in Figure 2-21.

![Figure 2-21: Representations of a stock, flow, converter, and connector (Martin, 1997)](image)

“The symbol for a stock is used to represent anything that accumulates or drains (e.g., water accumulating in the bathtub). A converter is used to take input data and manipulate or convert input into some output signal” (Martin, 1997). “A connector is an arrow that allows information to pass between two converters, stocks and converters, stocks and flows, and converters and flows” (Martin, 1997). Development of a mathematical equation combines two fundamental ideas (Roberts, 2001). First, the general equation to calculate present value of the stock (Figure 2-22) at any moment in combination with the past status generates future stock. Second, the flow occurring over a onetime interval equals the length of the interval, multiplied by the rate of flow per time interval.

![Figure 2-22: Change of stock over time (dt)](image)
Combination of these two ideas produces an equation of present stock at any time (t):

\[
\text{Stock at any moment } (t) = \left[ \sum (\text{all inflows}) - \sum (\text{all outflows}) + \text{initial value} \right] \\
= \int_{0}^{t} \left( \text{Stock variable} \right) \, dt
\]

2.4.3 The feedback effects of decisions

Feedback is a process whereby an initial cause ripples through a chain of outcomes ultimately to re-affect itself. On the other hand, a closed-loop system, is a circular chain of causality that “feeds back” to itself (Martin, 1997).

Feedback systems are most commonly called as closed-loop systems. In a feedback system, each variable is the cause and the effect simultaneously. In a feedback system, a change in the environment leads to a decision that results in an action affecting the environment and thereby, influencing future decisions.

Feedback systems can be either positive or negative. The term “positive” indicates changes in the feedback system that move in the same direction to produce compounding (reinforcing) behavior. The term “negative” indicates changes in the feedback system that move in opposite directions to produce balancing (stabilizing) behavior.

2.4.3.1 Positive feedback system

Positive feedback causes growth and change (Martin, 1997). A positive feedback loop can be demonstrated by the example of a Biology research assistant growing bacteria in a shaking flask (Figure 2-23). Reproduction increases the number of E. coli bacteria. The higher reproduction rate will reproduce more bacteria in the flask. The reproduction rate is directly dependent on the number of bacteria already in the flask.

![Diagram of Positive Feedback System]

Figure 2-23: Positive feedback (Martin, 1997)
The shaded arrows in Figure 2-23 are the causal links and not information links or material links. The flow of bacteria reproduced each hour, into the stock of collected bacteria is indicated through a material link (Martin, 1997). The information link that links the reproduction rate to the current number of bacteria is called as a connector. The information about the current state of the system (the value of the stock) is carried to the mechanisms that causes the system to change (the flow) thorough the connector. The behavior of the system over time is determined with help of material and information links.

The behavior of the E. coli bacteria obtained is shown in Figure 2-24 after the model in Figure 2-23 is run in STELLA. The population grows from 100 to 25,600 bacteria in four hours.

### 2.4.3.2 Negative feedback system

Negative feedback stabilizes systems by negating the change (Martin, 1997). An increase in a variable finally leads to a decrease in that variable in a negative feedback loop. The gradual decay of radioactive nuclei is one example of a negative feedback system. There is a fraction of total number of radioactive nuclei decay every year. Figure 2-25 depicts a radioactive decay structure.
The decay rate causes the stock to decrease by constantly drawing nuclei out of the stock of accumulated nuclei. Initially, the number of radioactive nuclei is large. Because of the large number of nuclei, the decay rate is large. A large decay rate reduces the number of nuclei (Martin, 1997). Now a smaller number of nuclei remain, and the number is still significant. The decay rate is still high, but lower than before. As nuclei continue to decay, and become fewer and fewer. Due to the decay of nuclei, the process becomes slow. Figure 2-26 replicates the behavior of the radioactive nuclei, modeled in STELLA. The behavior shows an asymptotic decline and is called exponential decay.

2.4.4 System boundary

System dynamics is concerned with the behavior of a system over time. In every feedback system, the behavior of interest is generated within a closed boundary. A modeller must clearly define the model boundary while creating a system dynamics model of a feedback
system (Martin, 1997; Albin, 1997). The model boundary consists of all components present in the final model.

It is important to understand dynamic complexity and not detailed complexity. While defining a system, one needs to be aware of the level of details. Generalization is often the key to understanding complex systems. Figure 2-27 illustrates the need for proper choice and number of variables in order to reduce the complexity in understanding a system properly (Roberts, 1983). This happens because the ability to grasp the total dynamic of the problem becomes weaker as we add more variables.

![Figure 2-27: System complexity (Roberts, 1983)](image)

### 2.4.4.1 Defining variables

The modeller must separate the initial components listed into two important groups to further specify a model boundary:

i) Endogenous - dynamic variables directly involved in the feedback loops of the system

ii) Exogenous - components whose values are not directly affected by the system

Then he/she needs to specify components as stocks and flows. Exogenous components are usually time varying constants or constants parameters. They are not stocks or flows. Stocks are accumulations (Albin, 1997). Exogenous components can be visualized and measured, such as population. But, they can also be abstract, such as level of fear or reputation. Changes in stock are known as flows. They are measured in units of the stock over time and termed ‘rates’. Common examples of flow are birth rate, death rate, and shipping rate. Value of exogenous component does not get affected by any change in values of stock or flow.

Exogenous components are termed ‘quantitative variables’. Another stream of variables is dependent variables. Their values are dependent on the values of other variables in the system and determined by one or more other variables in a function (Yuan et al., 2012). The
last type of parameter is qualitative variables value obtained through survey, such as questionnaires, interviews, on-site visits, etc.

2.4.5 Causal loop diagrams
The technique of describing positive and negative feedback processes is known as causal loop diagramming in the field of system dynamics modeling (Coyle, 1996). Causal loop diagrams form closed loops and describe the map of cause and effect relationships between individual system variables (Radzicki et al., 1997) due to linkage. After the necessary information for the goals is specified and the system boundary is defined, a hypothesis is developed and causal loop is drawn.

Positive and negative causal loop
A generic causal loop diagram is presented in Figure 2-28. The existence of a cause and effect relationship is indicated by the arrow linking each variable. The direction of causality between the variables is indicated by the plus or minus sign at the head of each arrow (Radzicki et al., 1997). A plus sign indicates that the variable at the tail of each arrow causes a change in the variable at the head of each arrow following the same trend (reinforcing) and minus indicates the opposite trend (balancing).

![Figure 2-28: Causal loop diagram of positive feedback system](image)

A symbol in the center in a causal loop diagram indicates the overall polarity of a feedback loop, whether the loop itself is positive or negative. This overall positive or negative effect can be seen by tracing through the loop. A generic causal loop diagram of a negative feedback loop structure is presented in Figure 2-29.
Figure 2-29: Causal loop diagram of negative feedback system

If variable A fall due to an external ripple effect, variable B would move in the opposite direction as variable A (i.e. rise), variable C would move in the opposite direction as variable B (i.e. fall), variable D would move in the opposite direction as variable C (i.e. rise), and variable A would move in the same direction as variable D (i.e. rise). The rise in variable A after the ripple effects around the loop move it back towards its state prior to the shock i.e. acts to stabilize the system,. The overall ripple is thus counteracted by the system's response (Radzicki et al., 1997).

Causal loop diagrams are generally used for explaining the model feedback behavior. These are particularly helpful to present the important ideas of the already created model (Richardson, 1986). Type of flow (information or non-information flow) cannot be distinguished through a causal loop diagram. As a result, they do not represent the direct causal relationships between flows and stocks.

2.4.6 Reference modes
A plot of the behavior of key variables of a system over time helps in understanding the general behavior of the system and is useful for the system reference (Albin, 1997). Time is plotted on the horizontal axis and units of the variables on the vertical axis (Figure 2-30). The time plots of the key variables are often quite useful in analysing the behavior of the model before and after building of the model. The reference mode is helpful in getting clues to model the structure appropriately by capturing historical data on paper, and can check acceptability after the model is built (Sterman, 2000).

There are two types of modes that are created during conceptualization:

- Historically observed modes, and
- Hypothesized reference modes

Historical reference modes are created by using the historical data. Comparison of model output to the historical reference mode helps in validation in later stages of model
construction. The model needs rework if it is not capable of producing behavior similar to historical observations (Radzicki et al., 1997). Figure 2-30 shows a historically observed reference mode combining positive and negative loops for a construction process. Historical reference modes use historical data.

![Figure 2-30: Pattern of behavior of a construction process (s-shaped growth)](image)

The speculated reference mode is a simplified curve (Figure 2-31), typically drawn by hand, consisting of the key features of the behavior pattern of the important system components (Kirkwood, 1998). Sketching of a hypothesized curve is performed by inserting the key features of the variables from the given system details. Exponential growth; exponential decay; overshoot and collapse; S-shaped growth; and damped, sustained, and expanding oscillations are the common hypothesized reference mode behaviors.

![Figure 2-31: Common system behaviors (Kirkwood, 1998)](image)

2.4.7 SDM for construction management

Project management is one of the more complex and poorly understood areas. Delays and cost overruns are rules rather than exceptions in construction, product development and software development (Sterman, 1992). Construction project suffers from numerous problems of costing and scheduling. Costly ripple effects are frequently generated through
customer design changes. As a consequence, it increases the work force, lowers productivity, and creates higher costs and costly litigations over responsibility for overruns and delays.

System dynamics has been demonstrated to be an effective analytical tool in project management, including on large scale projects in civil construction (Park, 2005; Sterman, 1992; Charitamara et al., 2002). Large scale projects are categorized as complex dynamic systems (See also 2.2.1). To manage such complexity properly, a model must be capable of representing systems with their complex relationships and characteristics (Sterman, 1992) such that they can be well understood by managers of the project.

2.4.7.1 Multiple interdependent components
Analysis of the process becomes complicated because of the interdependencies of variables. Change in one part of the system leading to implications in the other, remote parts (Sterman, 1992). It is possible to trace the causal impact of changes by capturing such interdependencies throughout the system.

For example, changing the location of a door in an engineering drawing may necessitate workers to be rescheduled from one task to another due to subsequent changes caused in other areas of electrical or HVAC system, etc. This may delay some tasks and accelerate others.

2.4.7.2 Construction dynamics
Construction projects are highly dynamic in nature. There are multiple time delays in executing the schedules, identifying and correcting errors, and responding to unexpected changes in scope of work or specifications. For example, the capability of an organization is benefited in the long run by hiring additional workers (Sterman, 1992). Productivity is affected due to the diversion of time of experienced workers from their work to train the recruits in the short term. Highly developed guidelines enable system dynamics to appropriately represent, analyze, and explain the dynamics of complex technical and managerial systems.

2.4.7.3 Multiple feedback processes
A complex system like a large construction project consists of multiple feedback processes interacting with each other. Feedback in construction management refers to the mechanism of self-correcting and self-reinforcing side effects of decisions (Sterman, 1992). For example, if a project falls behind schedule, one possible response may be to increase the use of overtime.
The extra hours help in bringing the project back on schedule, reducing the need of overtime in future through the self-correcting action of the feedback system. However, due to higher overtime for extended period, workers may become fatigued, which may lead to a higher error rate and lower productivity. Thus, there would be further delay in the project contributing to more overtime, in a self-reinforcing feedback process.

Traditional cost and scheduling tools such as critical path methods (CPM), and PERT and Gantt charts do not adequately account for feedback effects. The process of change in time required to complete a step of work is determined by CPM (Sterman, 1992). In case of change in the owner’s requirements or error necessitating rework during the construction process, re-estimation of time is performed on the basis of historic data, past experience, or judgement.

2.4.7.4 Nonlinear relationships

Nonlinearity refers to causes and effects that do not have simple, proportional relationships. Compared to any other formal modeling technique, system dynamics puts more emphasis on to the importance of nonlinearities in model formulation (Richardson et al., 1981; Forrester, 1987). For example, increasing work for an engineer from 40 to 44 hours per week may lead to adverse effects due to fatigue and errors caused by longer hours, even though output may increase by certain amount.

2.4.8 Applications of SDM in project management

Dynamic modeling is commonly used in construction management to understand the complex feedback process of the system (Chang, 1990; Lim, 1994; Rodrigues et al., 1998). However, SD developments in the construction field focus on separate subsystems of a traditional construction process such as different phases or human resource input to projects. Richardson et al. (1981) first developed a simple SD model in the area of general project management. This model was then modified by Chang (1990) for managing construction phase and, by Lim (1994) and Ogunlana et al. (1998) for managing design phase of a project. Other SD models include software project staffing (Hamid, 1989), parallel activities and project duration (William et al., 1995), the impact of client behavior on project development (Rodrigues et al., 1998), rework error in a project system (Love et al., 1999), design error induced rework in construction (Love et al., 2000), and dynamics of ‘design and build’ construction project (Charitamara et al., 2002). Yuan et al. (2011) proposed a model for simulating effects of various management strategies and change in traditional construction
culture and behavior on C&D waste reduction.

2.4.8.1 Schedule management
Rodrigues et al. (1998) used a SD model to investigate management and negotiation of schedule adjustments with the client to minimize the downstream effects of introducing requirement changes during the later design stages. Effects of complex client behavior on a project, such as schedule restrictions, high demand on progress reports, approval delays, and change to work scope were quantified in the study.

As a first step, he developed and calibrated the model to reproduce the steady behavior implicit in the plan. The second step was to use the model to explore the benefits of extending the schedule to reduce the negative effects of schedule pressure. It was found that beyond the 60% level, the quality of the designs did not improve significantly, while cost and schedule kept increasing (Rodrigues et al., 1998). Hence, an appropriate level of schedule adjustment would be around 60%. The main conclusion from this investigation was on the time of introduction of changes later in the design phase. For that, management must keep a tight schedule.

2.4.8.2 Design productivity arising from staff changes
A model of the design process was proposed by Robert (1998) to analyze the reasons of degradation of design productivity originating from staff changes. This paper modeled the impact of changes of prime project personnel during the design phase of a construction project. The change of key design personnel was found to be highly disruptive to communication and the lack of recognition. This eventuality resulted in a significant under-estimation of uncertainty. The impact of a main team member on the design process of a construction project was demonstrated by applying the concepts of system dynamics in this paper. Feedback effects of a combination of fragmented design processes, high demand for detailed information from multiple team members, expectations in delivery times, and the need for effective communication were also studied.

2.4.8.3 Dynamics of Design-Build construction project
A system dynamics model developed by Charitamara et al. (2002) incorporated major subsystems and their relationships inherent in Design and Build construction projects. The model was validated with a case study in Thailand. Relationships among the design, procurement, and construction functions were established to understand the dynamics of the
D-B project. Extensive simulations with many policies, individually or in various combinations, showed that improvement in time or cost could be made with proper policy combinations. These combinations reflected strong interactions between the whole design-build systems.

In experimentation (Charitamara et al., 2002), it was found that the combination of a full overtime schedule, average material ordering, and fast track construction with moderate crashing of design was most appropriate to achieve overall improvement in both time and cost. To achieve the optimized cost of the project in D-B using traditional construction methods, extending the construction schedule, combined with material ordering based on actual need was the best solution.

A model of the design process was constructed by Ogunlana et al. (1998) and it incorporated most of the management problems: (1) making a profit/budget, (2) coping with schedules and deadlines, (3) scope change management, (4) intragroup communications, (5) quality control, (6) communication with client, (7) lack of experienced staff and/or project managers, (8) low fees, (9) scheduling/planning, and (10) time management. The model, when tested with data from two large design projects, replicated field practice well. Simulation showed that improvements could be made through changes in policy. The results of investigations with two design projects depicted the following policy structure for meeting project deadlines: (1) good control on progress, (2) allocation of efficient manpower, (3) accurate workload estimation, and (4) early realization of under-estimated work.

2.4.8.4 Error/Changes and rework

Cooper (1993) presented the concept of “The Rework Cycle” in a series of three articles to understand the nature of development projects. His studies found the rework cycle to be the most important single feature of the system dynamics project models. The rework cycle’s recursive nature created problematic behaviors and it often stretched out over most of a project’s duration. It was the source of many project management challenges. The rework cycle model developed is shown conceptually in Figure 2-32. Cooper (1993) identified the need for a ‘different view of development projects’. One recognized the rework cycle, planned for it, monitored it and helped managers to reduce its magnitude and duration.
Subsequent modellers have developed other rework cycles, principally Hamid et al. (1984). They retained the rework cycle’s recursive nature, but added other features or used other model structures.

Love et al. (2000) considered rework and changes as an interference with the intended progression of work, and described the way changes (and their actions or effects) can impact the project management system. Using a case study and the system dynamics methodology (Figure 2-33), the major factors influencing a project’s performance were observed and it was found that the need for understanding particular dynamics could deter the performance of a project management system.

![Figure 2-32: The rework cycle (Cooper, 1993)](image-url)
In an effort to address the issue of uncertain and complex behavior of a construction project because of iterative cycles caused by errors and changes, Lee et al. (2006) introduced an IT perspective of the dynamic planning and control methodology. The web-based DPM being a part of the dynamic design and construction project model allows the capturing of feedback processes caused by errors, changes, and the smooth transaction among geographically distributed participants during the design and construction processes.

Lynies et al. (2007) reviewed the history of adverse dynamics in project management in
context of existing modeled structures. They applied SD to specific areas of project management and provided policy messages and directions for future research and writing.

2.4.9 Application of SDM in waste management

2.4.9.1 Urban solid waste management

Sudhir et al. (1997) proposed a system dynamics model for a sustainable urban solid waste management system to study the effects of various policy and structural alternatives and its potential. He addressed several interdependent issues such as public health, present and future costs to society, environment, and the livelihood of the ‘actors’ in the informal recycling sector. This system dynamics model captured the dynamic nature of interactive actions among the various constituents of the urban solid waste management system in a typical metropolitan city in India.

Kollikkathara et al. (2010) developed a more complete and sophisticated simulation method for integrated assessment of complex municipal waste-management processes for the Newark urban region in the US. The results showed that the generation of municipal solid waste underwent an increase during the period of forecast, due to the increase in the extents of the determining socio-economic and population variables.

2.4.9.2 Concrete construction and demolition waste

A generic dynamic material flow analysis model was presented (Müller, 2006) and applied for the dissemination of concrete in order to know long-term changes of resource demand and waste generation in the Dutch dwelling stock for the period of 1900–2100. The model was applied to concrete, representing an important part of the overall construction inventory.

2.4.9.3 Onsite C&D waste management

A simulation model was developed (Hao et al., 2007) based on system dynamics methodology by incorporating the relationship of major activities essentially involved in C&D waste management for strategic planning of Construction and Demolition waste in Hong Kong which by incorporated the relationship of major activities essentially involved in C&D waste management.

Ye et al. (2010) proposed a system dynamic model for estimating the generation of C & D waste. This approach holistically considered the inter-relations and interdependences of factors within the C & D waste management process.
Summary (SDM in waste management)

It is evident that a few studies have identified the origins and causes of waste generation and contributory factors (Bossink and Brouwers, 1996; Gavilan and Bernold, 1994; Osmani et al., 2008b). Table 2-6 shows the summary of the research works carried out in the field of waste management applying system dynamics modelling.

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Type of waste*</th>
<th>Research objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudhir et al. (1997)</td>
<td>Urban solid waste</td>
<td>Structural and policy alternatives of the urban solid waste management system</td>
</tr>
<tr>
<td>Hao et al. (2007)</td>
<td>C &amp; D waste</td>
<td>Reducing waste to landfill by implementing on site sorting methods</td>
</tr>
<tr>
<td>Kollikkathara et al. (2010)</td>
<td>Municipal waste</td>
<td>Influence of socio-economic and population variables on urban solid waste</td>
</tr>
<tr>
<td>Ye et al. (2010)</td>
<td>C &amp; D waste</td>
<td>Interrelationship of management policies, landfill charges and staff training on waste generation</td>
</tr>
</tbody>
</table>

* C & D: Construction and Demolition

From the above literature review, it is clear that none of the researchers have focused on the influence of design change on generation of construction waste and waste management at the source during the construction process. Hence, it demands in-depth analysis of waste generation at the source as well as proper waste management in order to minimize waste generation and maximize reuse. This would reduce landfill load and recycling of waste materials. This would further decrease greenhouse gas emissions. A SDM model is developed to predict the potential waste. Some of the model structures presented in this study has their conceptual basis on previous SD models (Cooper, 1993; Ford and Sterman, 1998; Hamid, 1989; James et al., 2001; Marco A.D., 2010; Yuan et al., 2011).
2.5 Integration of BIM and SDM

The construction industry, like many other industries, needs to adopt advancements in technologies to overcome adverse impacts of construction waste. “Though focus on reduction of waste has been negligible over the past years, employing waste reduction strategies may still be the best approach towards minimizing the intensity of the construction waste problem” (Wimalasena et al., 2010). It is necessary to incorporate general strategies related to improving the managerial capacity at design, procurement, and production stages, including financial and nonfinancial measures, and to achieve economic benefits of an on-site waste management program (Carlos et al., 2002). It is understood that the construction waste management process must involve not only the site management team, but also the architect and engineers involved in the design process.

Traditional planning methods, such as the Critical Path Method (CPM) or Program Evaluation and Review Technique (PERT), do not allow experimentation in order to demonstrate appropriate policies and post-project analysis (Rodrigues and Bowers, 1996). However, the system dynamics approach has better flexibility for establishing a model, conducting experiments, and analyzing policy options (Lyneis et al., 2007). Large-scale construction projects are extremely complex and highly dynamic, and have multiple feedback and nonlinear relationships requiring both hard and soft data (Sterman, 1992). System Dynamics Modeling (SDM) can be used simultaneously with traditional techniques, serving as a tool to analyze strategic decision making by project management executives, thus complementing the planning techniques (Lyneis et al., 2007).

The digital database allows BIM to act as a virtual representative of a physical facility to perform qualitative and quantitative analysis. The BIM process continues throughout the lifetime of a facility (NIBS, 2010). From the above discussion, it is very clear that revisiting the BIM and associated process controls, variables, waste generation, and their minimization as well utilization is essential.

Almost all published research studies found in the literature failed to focus on the causes of construction waste generation and management of waste generation at source. To date, no methodology to minimize construction waste by integrating digital information of the project model and system dynamics is available. An event based pre-construction analysis method, which is capable of integrating virtual construction techniques and construction process dynamics to effectively reduce waste generation, is yet to be realized.
Chapter 3: BIM Based Methodology to Minimize Waste Rate of Linear Structural Components

3.1 Overview

Environmental sustainability has become a key focus for many industries. Sustainable development practices are well recognized and enforced by all governments (local and federal) in Canada. The construction industry, like many other industries, needs to adopt advancements in technologies to overcome adverse impacts of construction waste. Leadership in Energy and Environmental Design (LEED) is one of the most accepted and widely recognized sustainable building rating systems (Syal et al., 2007). Construction waste management often focuses on reuse, recycling, and proper disposal of waste materials at landfills. Waste reduction at the source is the best and most efficient method for minimizing waste. It eliminates many of the waste disposal related problems (Begum et al., 2006). However, the focus on reduction of waste at the source has been negligible in the past years. Waste reduction at the source may still be the best approach towards minimizing the intensity of the construction waste problem.

Traditionally, the building design process consists of two different objectives, i.e. architectural and structural designs. Architectural designing focuses on planning, designing spaces, and ambience. It considers functional, technical, social, and aesthetic aspects of the utility while structural design aims at the mechanics of the structural elements of a building. There is a close relationship between these two design processes. The architectural design defines the geometrics of the building elements and this information becomes key input to structural designs. On construction projects, reinforcement bars are generally purchased in standard lengths, and required bar lengths are normally shorter than the standard lengths with large length variations. Thus, success of a sustainable design process becomes highly dependent on efficient analysis among the two diverse design teams in order to optimize trim loss in structural elements of a building. It is possible to change the number and size of structural members up to some extent by rearranging building spaces. Coordinated modeling of these two design processes typically does not occur in the early design stage. Poor integration leads to uneconomical design and higher material waste (Chen et al., 2005). This difficulty is mainly due to lack of coordination and modifications in building models to cater to architectural and structural needs. BIM makes it possible to (i) coordinate among stakeholders in the building design process, (ii) to explore different design alternatives more
efficiently, and (iii) to avoid the time-consuming and error prone method of re-creating all
the building geometry due to a change in structural analysis and design. This challenge can
be overcome by creating structural and architectural objects from the same underlying
database. It facilitates faster repetitive modifications between the architectural and structural
designs and further analysis for losses due to trimming of rebar with an optimization tool.
This approach enables the design team to recursively modify the building model to analyze
the best cutting combinations of the available market lengths and special lengths of rebar.
While exploring different BIM structural modelling software programs, it has been noted that
these programs have limitations in producing an abstract of the rebar schedule with a count of
bar for a length of specific type (diameter, for example). Further, to obtain an accurate rebar
schedule, reinforcement placement in the BIM model has to exactly match with the actual
field work. For example, if trim loss is calculated by considering a continuous beam over
multiple spans, the main reinforcement bar should also be laid as a continuous member in the
model.

This work presents a case study that investigates a rebar trim loss optimization process using
an optimization algorithm within a structural BIM model. The model allows possible
reduction in total number of structural components in a building.

3.2 Trim Loss of Rebar
The USGBC LEED reference guide states that a typical North American commercial
construction project generates 12 kilograms of solid waste per square metre of floor space
(USGBC, 2011). According to the report on waste management for the construction industry
by the Canadian Construction Association, 8.1% of total construction waste generated
consists of metal, while 5.2% of metallic waste is generated from demolition wastes (CCA,
1992). Metro Vancouver, BC, has also estimated metallic construction waste at 0.09 tonnes
per 1000 ft² for high rise buildings and up to 0.21 tonnes/1000 ft² for institutional low rise
constructions (Metro Vancouver, 2008). Poon et al. (2004) have found that out of total
construction waste, reinforcement steel waste was 3-5% in public housing and up to 8% in
private residential construction as metallic waste. This metallic waste has recycling potential,
however, with an additional cost. In addition, rebar waste has a direct impact on the project
cost (Salem et al., 2007) which is much higher for reinforced concrete framed structures
involving major structural parts of the building as reinforced members.
In case rebar shaping is done using computerized numerically controlled (CNC) machines for rebar supplied in coils, the process produces few scraps with almost zero percent trim loss. However, CNC can be used for bar shaping up to a bar diameter of 16mm (Sun-Kuk et al., 2004). Generation of waste is inevitable if the rebar is supplied in straight market lengths for on-site fabrication. Rebar is produced in Canada in accordance with the National Standard of Canada CAN/CSA-G30.18-M92 for Concrete Reinforcement. The national rebar standard is approved by the Standards Council of Canada. Canadian code of practice commonly designates as numbers rebar with, with the corresponding diameter in millimetres in brackets, as: 10 (11.3), 15 (16.0), 20 (19.5), 25 (25.2), 30 (29.9), 35 (35.7), 45 (43.7), 55 (56.4) (CBSA, 2011). Rebar sizes are commonly referred to as the bar designation number combined with the letter "M" (metric) to distinguish from imperial bar measures in USA. Thus 10M refers to a bar designation number of 10 and a diameter of 11.3 millimetres. The standard lengths for rebar available in the market are 6 metres (20 feet), 12 metres (40 feet), and 18 metres (60 feet). Residential markets primarily use rebar of smaller diameter, while complex construction and fabrication markets use most of the larger sizes of rebar (CBSA, 2011). The standard market lengths produce relatively more scrap after the rebar is cut off as per the design schedule. Percentage cost ratio of waste increases with the increase in diameter of bar, even for a small trim length (Kim, 2002).

3.3 BIM as a Coordinated Design Analysis Tool

Building designers consider re-analysis and revising the designs a time consuming process. Most of the time, it leads to a model that might be impressive in architectural aspects but that leads to lack of integration, co-ordination, and collaboration between the various functional disciplines of a project. The BIM is a richer repository than a set of drawings and it is capable of storing objects, spaces, and facility characteristics in a digital database (Eastman, 1999) and helps achieving levels of coordination far in excess of the current norms (Schlueter et al., 2009). These BIM enabled qualitative and quantitative analyzes significantly enhance the efficiency of structural design, energy consumption, and other simulations of the building process. It provides a superior 3D modeling environment compared to 2D CAD (Fu et al., 2006) and has the ability to parametrically capture design intent, which rapidly performs iterative changes and reduces the likelihood of coordination errors. The parametric modeling property keeps changes made anywhere in the model updated all the time and this updating makes re-analysis and revisions of designs fast and simple. Since BIM represents virtual true
space, its clash-detection-process can check intersecting volumes. A 4D BIM scheduling application can link CPM schedule activities to 3D objects. Cost data can be associated with each element resulting in a detailed cost schedule (Popov et al., 2010). 3D objects can also be linked to a variety of source documents via hyperlinks, which enable the model to function as a graphical information system (GIS) for the building (Isikdag et al., 2008; Li et al. 2005). Process simulation creates a virtual feedback loop such that design and construction coordination challenges and sequences can be identified prior to commitment of field process.

3.4 Rebar Waste Optimization Approach

The virtual environment of BIM enables identification and implementation of desired changes, through the increased visibility and predictability, earlier in the design process. This, in effect, encourages experimentation and collaboration to stimulate free exchange of ideas to exercise better control over the project cost, and to achieve significant improvements to reduce waste at source. Figure 3-1 and Figure 3-2 show the structural model created out of the underlying architectural BIM database without requiring any extra efforts.
Traditionally, a structural engineer starts the design process by interpreting architectural drawings, as a separate step, with the focus on analyzing the mechanical properties of building elements and structure. The analytical models for structural analysis are then reproduced with respect to general framing layout and section properties suggested in architectural designs.

In the proposed approach, structural members of the building are created out of the same architectural model by assigning structural property to the members and then analyzing them for trim loss optimization. The engineer shares the same underlying building database for structural design to make changes quickly. The design team explores design changes, and develop and studies several design alternatives to make key design decisions. Each option is substituted into the model for visualization and quantity take-offs, to help the designer work with rebar optimization analysis. Figure 3-3 shows the authors’ suggested approach to collaborative building design with the BIM models.

First, the architect proposes the building design concept based on the requirements of the owner, building bylaws, and code of practice. The BIM model is then created by incorporating structural elements (i.e. beams and column positions). An interference check of structural and architectural objects is performed before the structural analysis (integration of building spaces and structural elements). The structural elements are then checked for possible modifications in the dimension of the members and reduction in the total number of structural members such as columns, beams, and footings. The architect then reviews and incorporates the changes in the model. Structural analysis is then performed on the same model database, and the structural BIM model is developed. The detailed bar bending schedule generated by BIM is then used for rebar optimization analysis with one dimensional (1D) stock optimization tool to identify possible trim losses related to available market lengths. In this research 1DNest software (ODO, 2011), developed by using a mix of simulated annealing heuristic algorithms was used to analyze the best combination of rebar lengths.
3.5 Steps for Early Rebar Optimization

Under the proposed approach, rebar waste analysis should be conducted by the design engineer in three steps:

(i) Available market length
First, the detailed structural BIM model is created by considering the reinforcement bar lengths available in the market. BIM allows the designer to detail bar placement with splices, hooks, and bends in a 3D environment. For example, beam lengths along 5 and 6 for length A to H (Figure 3-5) are provided with 2 numbers of 20M bars at bottom for 3 beam lengths. If 6.10 m market length is used, then, 2x3=6 bar of length 3.86 m will only be required as cut-off length.

(ii) Special ordered length
A similar analysis as mentioned in step (i) is performed for the special rebar lengths available with the manufacturer. Percentage waste is calculated for combinations of standard market
iii) Modify the design

At the third step, a designer reviews the geometry of the structural members. For example, continuous beams may result in fewer cut-off lengths (Figure 3-6). Similarly, repeated structural members (such as beams repeated in an apartment for 10 apartments on a floor in a 20 floor construction) are checked for rebar waste optimization. Structural arrangement of column footings is also reviewed for any special structural needs, such as combined footings, which need more reinforcement than usual.

In addition to the above, the design engineer should also check for any minor modifications in the arrangement of spaces and facilities, by which material requirement for construction can be reduced. The architect may work on the model based on feedback from ‘MEP’ and ‘HVAC’ design teams. This saves repetitive modeling and designing tasks among the multi-discipline design team and avoids errors due to manual coordination between structural engineers, architects, and drafters (James et al., 2008).

The above steps are repeated until the design team achieves the final optimum building model. Finally, structural drawings for the fabricator and construction documents for the engineers are generated from the final building model for use at the construction site.

3.6 Case Study

A case study to explore rebar trim loss optimization was conducted on a four unit, two storey reinforced concrete structure. The initial proposed building plan, as per the owner needs, is as shown in Figure 3-5. This building plan resulted in a repetitive beam layout for plinth, ground floor roof, and first floor roof levels. An irregular shift in the four units was proposed to provide aesthetic beauty to the building and to restrict vision through windows (e.g. for kitchen window W4) from outside the building.

As shown in Figure 3-4 the rebar waste optimization process has three steps.

(1) The first step was to prepare the structural BIM model and analyze it for possible reduction in number and size of structural members which resulted in minimum quantity of material (steel and concrete) required in the construction.

(2) The second step was to analyze the trim loss percent for i) market rebar lengths, ii) special rebar lengths, and iii) adjustment of dimensions of the structural members.
(3) Finally, an integrated optimal BIM model was prepared. This model was further checked for interference collision for building elements with MEP and HVAC elements.

During the process in each step, the structural engineer communicated his feedback to the architect through the BIM model, and in turn the architect quickly submitted his feedback with changes in the BIM model.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Steps for early rebar waste optimization}
\end{figure}

### 3.6.1 Initial structural analysis

The initial layout plan of the reinforced concrete framed structure described in this paper was originally available in traditional 2D CAD. Structural analysis and the design process were performed after the finalization of all architectural design works and completion of the bidding process. In this approach, the BIM model was prepared using Autodesk ‘Revit Architecture’ because of its interoperability with existing data with AutoCAD. The structural model was created from the underlying BIM database, using Autodesk ‘Revit Structure’.

The architectural plan originally suggested by the architect resulted in the following structural layout (Figure 3-5):
column and beam arrangement, repeated for four units

columns shown in hatch continued to ground floor roof level, while columns shown in dark continued to second floor roof level

columns around the stairwell went to even higher level and supported the overhead water tank above the second floor roof level

plinth beams were to support the load of 200mm thick walls and plinth slab

Figure 3-5: Structural arrangement of plinth beams and columns for initial analysis

Based on this architectural model the first structural model was developed with the following features:

- discontinuous beams (along grid 5, 6) with the beams resting over other beams, creating point loads on the main beams (PB5, PB14)
- depth and reinforcement of beam PB3 was more due to increased bending moment and shear force (due to point load from beam PB14)
- size and reinforcement of beam PB14 could not be reduced due to minimum requirements of structural code of practice

Rebar available in 6.1m and 12.2 m market lengths could not be used as single bar in most of the beams (for top and bottom reinforcement) due to shorter beam lengths. This further increased the number of 90° hook length at the ends of beams and rebar trim loss.

With the structural engineers’ feedbacks, a revised architectural model was proposed to address these rebar waste issues by suggesting slight modifications in the spaces shown in Figure 3-6a. This allowed structural engineer to propose continuous structural beam members. The structural BIM model was modified and analyzed for the feedback and architectural modifications (Figure 3-6b).

![Figure 3-6: (a) Revised building plan (b) Revised plinth beam plan](image)

In the next step, structural analysis was performed and found that column footings A4, B4 and C5 had overlapped soil bearing area, creating combined footing for these three columns. This needed higher depth and reinforcement compared to isolated footing and led to an
uneconomical section (Bangash et al., 2003). The savings in steel and concrete quantity were achieved by shifting the column positions to get an un-overlapped bearing area of footings. The feedback was then re-analyzed in the architectural BIM model and the building plan was modified by arranging the main door entry to the west instead of from the south, omitting one column C4 out of three columns which created a combined footing. BIM’s ability to coordinate changes and maintain consistency, called bidirectional associativity, updated the structural model components automatically.

3.6.2 Trim loss analysis

The next step in the process was to re-import the updated analytical model from architectural BIM, with the architect’s feedback, into structural BIM (Revit structures) and analyze it for structural requirements. After the structural design, a detailed reinforcement model of the structure in BIM was developed (Figure 3-7). The rebar schedule created automatically in BIM was then exported to MS Excel for the trim loss optimization process. Figure 3-8 shows the process of optimizing BIM model for rebar waste. Trim-loss quantity of rebar for available market lengths and special lengths used were calculated using ‘1D Cutting Optimizer’ software. Alternatives to optimize waste were worked out and further checked for possible changes in the layout of the structural members and their longitudinal arrangements. The whole analysis could be performed quickly on the same day, which would allow starting foundation works at site as per the schedule.
At the last step, a structural BIM model, which generated a minimum waste ratio, was proposed and fabrication drawings were created from the latest structural model to work at site.

Figure 3-8: Structural modelling for trim loss optimization

Rebar optimization analysis was performed for each potential construction phase (plinth, ground floor, first floor phase) in the sequence of the construction work to be carried out at site (for example construction of foundation before construction of plinth beams; laying first
floor slab before laying ground floor slab, and so on). This facilitated coordinated purchase of the rebar and planned inventory management in different stages of construction. The structural BIM model was created to generate the rebar schedule for the following stages:

a) Footings and columns up to plinth height
b) Plinth beam and plinth slab
c) Ground floor columns and stair
d) Ground floor ‘roof beams’ and ‘roof slab’
e) First floor column and stair
f) First floor ‘roof beams’ and ‘roof slab’

Each structural member needed different rebar detailing depending on the rebar placement arrangement and type of the structural member. For example, column reinforcement had a fixed length according to storey height while many alternatives were available for beam reinforcement depending on bar types (bent bar, straight bar) and number of spans (single span and multiple). In this case study, trim loss analysis was done for plinth beams to test the feasibility of the proposed approach. After working on the structural feedback, the final building model was proposed and optimization analysis was performed. The general reinforcement arrangement for the beams is shown in Figure 3-9.

![Figure 3-9: Reinforcement detailing of plinth beam](image)

The main bar sizes used in this case study was 15M and 20M. The 10M bars were used for stirrups throughout. Comparison of trim loss for each design alternative is made for the conditions when beam main reinforcement is placed a) column to column and b) continuous over supports. For high yield strength deformed bars, 90 degree hooks were considered at the ends, and basic development length (Equation 3-1) was calculated as per the structural detailing code of practice of the Canadian Standard Association (CSA A23.1) using the
relation:

\[ l_{hb} = 100 \frac{d_b}{\sqrt{f_c^*}} \]  

(3-1)

Where,

\[ d_b = \text{diameter of bar} \]

\[ f_c^* = \text{compressive strength of concrete} \]

Length of splices was taken as 40 times the diameter of the bar.

For the case when beams are considered as continuous over support, the number of rebar lengths (Eq. 3-2, 3-3 and 3-4) required was calculated by the relations:

\[ L = S - 2c - 2h \]  

(3-2)

\[ N = \frac{L}{l} \]  

(3-3)

\[ L_e = (N - i) \times l + (i \times s) \]  

(3-4)

Where,

\[ L = \text{total lengths required} \]

\[ L_e = \text{cut-off length at the end} \]

\[ N = \text{number of market lengths required} \]

\[ l = \text{market length of rebar} \]

\[ h = \text{hook length (i.e. } l_{hb} \text{) } \]

\[ l_{hb} = \text{basic hook length} \]

\[ c = \text{clear cover to reinforcement} \]

\[ S = \text{beam length (continuous or support to support)} \]

\[ s = \text{splice length} \]

\[ i = \text{integer value of } L \]

Structural BIM is capable of handling most of the code of practice in use. Table 3-1 shows the results of calculations done by using relations (3-2), (3-3), and (3-4) for the plinth beam plan. Calculation of rebar quantities for beam PB13 and PB14 at grid 5 and 6 are shown in Figure 3-10. Hook length as per CSA A23.1 is calculated as 300mm and splice length as 800mm. The total length of 20M main bars came to 19160 mm, for which three lengths of
6100 mm and end bar length of 3860 mm were required. The total number of bar lengths required is shown in Table 3-1.

\[
\text{end bar length} = 800 + 2760 + 300 = 3860 \text{ mm}
\]

![Figure 3-10: Calculation of rebar schedule quantities](image)

Table 3-1: Revised Schedule for Plinth Beam Plan (Figure 3-6b)

<table>
<thead>
<tr>
<th>Bar Length (mm)</th>
<th>Count</th>
<th>Bar Length (mm)</th>
<th>Count</th>
<th>Bar Length (mm)</th>
<th>Count</th>
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<tbody>
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<td>1395</td>
<td>6</td>
<td>865</td>
<td>4</td>
</tr>
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<td>2240</td>
<td>6</td>
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<td>4</td>
<td>1770</td>
<td>16</td>
<td>2516</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1830</td>
<td>4</td>
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<td>6100</td>
<td>44</td>
<td></td>
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</tbody>
</table>

Considering the practical aspect of laying reinforcement cages, it was assumed that 20 feet (6100 mm) of market lengths are used at site, and trim loss comparison was compared for all the available market lengths of 12200 mm and 18300 mm. Table 3-1 shows the rebar schedule obtained based on the calculations as per equations, and created in the BIM model.
accordingly. Rebar lengths of 20M bar type and their total count used was extracted from the BIM model for optimization of trim loss when 300 pieces of 12200 mm long rebar are purchased from the market. Cost per meter length was used for assigning weight to the source bar when different source rebar lengths were used. For example, when cut-off length (rebar from waste) available at site was used, it was assigned a ‘cost’ value of less than 100, which is a dimension less number (say 75) to give less priority to this cut-length to be used in optimization calculations and not to generate another waste piece from a fresh length. Cut allowance for cutter blade thickness was assumed negligible compared to the total length of the bar. Trim length longer than 300mm was assumed to be reused in further construction works at the site (known as cut-off length).

Table 3-2 and Table 3-3 show the results of cutting patterns for 6100 mm (20’) and 12200 mm (40’) rebar lengths and 10M, 15M, and 20M type bars, which are most frequently used in the project. Table 3-2 is combination list for 6100 mm bar length. Rebar combination generates a maximum material loss of 0.256%, 7.36%, and 7.11% for 10M, 15M, and 20M bars respectively. Table 3-3 shows maximum 0.256%, 1.4%, and 0.93% material loss with 12200 mm long rebar are used respectively for 10M, 15M, and 20M bars. All the above percent material loss includes reusable cut-off lengths greater than 300 mm long. These lengths will not be recycled and reused in the work as extra bars, which are required to provide negative reinforcement at the beam-column junctions and slab edges. Figure 3-11 shows the comparison of estimated trim loss of the three rebar market lengths used in the optimization process.
The dominant length in the rebar fabrication of plinth beam is 12200 mm for all three bar types. The 10M bar has no effect of length variations because of less variety and smaller lengths for major quantity used as stirrups.
Table 3-2: Trim loss waste produced when 6100 mm market length was used

<table>
<thead>
<tr>
<th>Bar</th>
<th>Bar Type : 10 M</th>
<th>Bar Type : 15 M</th>
<th>Bar Type : 20 M</th>
</tr>
</thead>
<tbody>
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<td>Qty</td>
<td>Cutting Pattern</td>
<td>waste (mm)</td>
</tr>
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<td>2</td>
<td>1847</td>
<td>3x1150 2x763</td>
</tr>
<tr>
<td>B02</td>
<td>2</td>
<td>1847</td>
<td>2x1150 2x975</td>
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<td>5x1150</td>
<td>350</td>
</tr>
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<td>3</td>
<td>2400</td>
<td>1754</td>
</tr>
<tr>
<td>B11</td>
<td>4</td>
<td>2288</td>
<td>1640</td>
</tr>
<tr>
<td>B12</td>
<td>3</td>
<td>1540</td>
<td></td>
</tr>
<tr>
<td>B13</td>
<td>1</td>
<td>1540</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>264</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Material Used: 1606.3 Metre
Material to Order: 1610.4 Metre
Waste: 4.10 Metre (0.256%)

Material Used: 613.6 Metre
Material to Order: 658.8 Metre
Waste: 45.2 Metre (7.36%)

Material Used: 592.3 Metre
Material to Order: 634.4 Metre
Waste: 42.1 Metre (7.11%)
Table 3-3: Trim loss waste produced when 12200 mm market length used

<table>
<thead>
<tr>
<th>Bar</th>
<th>Bar Type: 10 M</th>
<th></th>
<th>Bar Type: 15 M</th>
<th></th>
<th>Bar Type: 20 M</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Qty</td>
<td>Cutting Pattern</td>
<td>Waste (mm)</td>
<td>Qty</td>
<td>Cutting Pattern</td>
<td>Waste (mm)</td>
</tr>
<tr>
<td>B01</td>
<td>1</td>
<td>2x1847 4x1150 4x975</td>
<td>6</td>
<td>22</td>
<td>2x6100</td>
<td>0</td>
</tr>
<tr>
<td>B02</td>
<td>2</td>
<td>1847 9x1150</td>
<td>3</td>
<td>1</td>
<td>5890 4610 1640</td>
<td>60</td>
</tr>
<tr>
<td>B03</td>
<td>1</td>
<td>9x1150 2x763</td>
<td>324</td>
<td>3</td>
<td>5890 4610 1540</td>
<td>160</td>
</tr>
<tr>
<td>B04</td>
<td>1</td>
<td>6x1150 2x763</td>
<td>3774</td>
<td>6</td>
<td>4610 4120 2066 1395</td>
<td>9</td>
</tr>
<tr>
<td>B05</td>
<td>127</td>
<td>4x1150 8x950</td>
<td>0</td>
<td>2</td>
<td>4610 4120 1830 1640</td>
<td>0</td>
</tr>
<tr>
<td>B06</td>
<td>3</td>
<td>4610 4070 2x1754</td>
<td>12</td>
<td>4</td>
<td>4070 3860 2516 1736</td>
<td>18</td>
</tr>
<tr>
<td>B07</td>
<td>4</td>
<td>4610 3860 2x1770</td>
<td>190</td>
<td>1</td>
<td>3860 3x2756</td>
<td>72</td>
</tr>
<tr>
<td>B08</td>
<td>4</td>
<td>4610 2400 2x1770 1640</td>
<td>10</td>
<td>1</td>
<td>2x3740 3195</td>
<td>1525</td>
</tr>
<tr>
<td>B09</td>
<td>1</td>
<td>4610 2288 2x1830 1640</td>
<td>2</td>
<td>1</td>
<td>3x3195</td>
<td>2615</td>
</tr>
<tr>
<td>B10</td>
<td>2</td>
<td>2x4070 3860</td>
<td>200</td>
<td>1</td>
<td>3195 2x2756 2x1736</td>
<td>21</td>
</tr>
<tr>
<td>B11</td>
<td>2</td>
<td>2x4070 2288 1540</td>
<td>232</td>
<td>2</td>
<td>3195 2x2516 2240 2x865</td>
<td>3</td>
</tr>
<tr>
<td>B12</td>
<td>1</td>
<td>4070 5x1540</td>
<td>430</td>
<td>8</td>
<td>2x2756 2x2516 1640</td>
<td>16</td>
</tr>
<tr>
<td>B13</td>
<td>1</td>
<td>2x2288 1540</td>
<td>6084</td>
<td>6</td>
<td>2x2756 2x2516 1640</td>
<td>16</td>
</tr>
</tbody>
</table>

Total: 132
Material Used: 1606.3 M
Material to Order: 1610.4 M
Waste: 4.1 Metre (0.256 %)

51
Material Used: 613.6 M
Material to order: 622.2 M
Waste: 8.6 Metre (1.40 %)

49
Material Used: 592.3 M
Material to Order: 597.8 M
Waste: 5.5 Metre (0.93 %)
A significant variation in waste with length is observed for 20M bar due to a variety of length combinations used as extra negative and positive reinforcement at supports and midspans. Therefore, further optimization is possible in case of 20M type bar with the use of special lengths and available cut-off lengths. For example, 20M rebar waste of 5.5 m reduces to 1.36 m (5.5-1.525-2.615) when 1.525 m and 2.615 m long trim lengths are reused in further construction works. This makes actual waste equal to $1.36/592.3 = 0.229\%$. Figure 3-12 shows the percent waste further reduced by combination of source bars with 12200 mm market length and available cut-off lengths to 0.113%, 0.341%, and 0.229% for 10M, 15M, and 20M bars respectively. This shows that waste of material as high as 1.6% can be saved when proper bars in market length are selected for combination and longer lengths.

![Figure 3-12: Waste ratio with combination lengths of source bar](image)

Following are the conclusions derived during the design process to maximize the benefits of the modeling and optimization process:

- Refine BIM Model accurately through coordinated design process in the design stage
- Design continuous structural members with longer lengths
- Use similar size (diameter) of rebar for main reinforcement
- Model geometry to avoid special structural members (e.g. doubly reinforced beams)
- Create BIM according to the construction stages at site
- Place exact reinforcement in the BIM model to reflect actual fabrication

This method gives more cost effective results if larger rebar size is used. Study showed that trim loss for 20M bar was reduced from 42.1m to 5.5m, with a total saving of 36.6 m per
The maximum cost saving was observed for 20M bars.

### 3.6.3 Summary

The objective of this research was to extend BIM into construction waste management to minimize rebar waste. The main contribution of this paper is to introduce a novel methodology to minimize rebar waste at the project design stage by analyzing the BIM models quickly with optimization techniques. Since waste due to trimming of steel rebar is considered to be one of the main contributors to construction waste, steel rebar waste has been chosen to be the focus of this research. The cutting losses of reinforcement bars could be reduced substantially by better planning and optimization techniques.

Generally, SA models are successful in complex combinatorial optimization problems through controlled randomization. For this reason, a simulated annealing heuristic approach has been proposed to solve the cutting stock problem in the construction industry. The waste optimization model has been validated with a case study. The model is successful in reducing the cost and amount of cutting losses. The method has the advantage of accounting for influence of rebar market lengths on the design changes. This method gives more cost effective results for rebar with a higher diameter because cost increases with increase in diameter for even smaller cut-off lengths. The model is capable of handling any kind of reinforced concrete framed structure.
Chapter 4 : Integration of BIM and SDM to Minimize Waste at Source

4.1 Overview
The issues of coordination, communication, complexity, and constructability are more likely to have an immediate impact on reducing waste in the majority of cases. Good practice is to add performance requirements and procurement actions to reduce waste at source in the policy describing the organization’s commitment to reduce waste. The improvements in management capacity of waste reduction lead to adoption of new tools and technology directly, such as an integrated BIM process. The present study demonstrates that critical categories such as design change and/or error, defective work and rework, and poor coordination, can contribute to considerable waste in a construction project.

This Chapter aims to discuss a prediction model developed to assess the generation of construction waste at source and the pattern of generation due to change in scope of work in a dynamic system. In this section, a System Dynamic Model (SDM), which can predict the waste in integration with a Building Information Model (BIM), is presented.

4.2 Waste Management at Source
As mentioned in section 2.1 and 2.4.9, all the reviewed methods are incapable of predicting the “time variable nature” of waste generation due to changes in scope of work and designs. The proposed methodology in this section integrates the BIM data with System Dynamics in order to predict construction waste generated at source due to change in scope of work, rework, lack of coordination, and poor integration of building subsystems, by considering construction project dynamics. The parametric engine of BIM makes it possible to generate revised material quantities created due to change in scope of work during the construction process. This revised material quantity information is modeled by mapping with the dynamic factors, which influence waste generation during project lifecycle, to predict waste quantities.

4.3 Framework of the Proposed Approach
The proposed integrated BIM and SDM approach to minimize waste at source is outlined in Figure 4-1. When a change in scope is directed, the BIM model is revised to incorporate the design changes. The BIM model is then analyzed in coordination with the AEC team to obtain the revised data pertaining to schedule, cost, and material required. The clash detection process is performed to find out if there any conflicts among the building components. Dynamic analysis is then performed by plugging the data obtained through BIM
analysis, the field, and the literature into the SD model.

The steps of the framework approach are as detailed below:

**Step 1: Revision of the BIM Model**
In this integrated approach, the BIM model is prepared and coordinated during the pre-construction stage of the project. During the construction process, when a change in construction is initiated, the BIM model is revised with the requested changes. The parametric relationship among the building elements automatically coordinates and manages the changes made to the building model.

**Step 2: Coordination of BIM**
BIM is then analyzed through the coordination of the AEC. The clash detection process is performed and checked for any discrepancies in the revision. The BIM scheduling application (time as the 4th dimension) links Critical Path Method (CPM) schedule activities
with 3D objects in a BIM model. Cost data is associated with each element of the BIM model, to generate a detailed cost schedule. Any change in the design resulting from a change in scope of work is compared with estimated quantities to obtain the difference in quantities before and after the change. Latest rates for the extra quantity of work are obtained from sub-contractors to know the cost of extra work.

**Step 3: Evaluation of Impacts**

Extra fractions of materials required during a particular construction phase due to reconstruction are analyzed with time for different variables (Figure 4-2). Values for all the variables (Appendix B) obtained from BIM (step 2), literature and the field observations are used to run the SDM simulations to predict waste, time and cost overrun. The SDM model in this research is validated by comparing the simulation results with actual project data.

![Integration of BIM and SDM](image)

**Figure 4-2: Integration of BIM and SDM**

**4.4 The SD Model Development**

The model for evaluating the effects of managerial strategies on C&D waste reduction at source proposed in this study is visualized through the STELLA software package. The STELLA software package is specifically produced for system dynamics modeling by isee.
systems Inc. (2010). It allows the structure of a process to dynamically visualize and communicate the real working of complex systems and ideas.

The general construction procedure specified by Barrie and Paulson (1992) used in the current modeling to derive the overall D-B-B system has five important subsystems controlling D-B-B construction dynamics: (i) construction progress, (ii) material procurement, (iii) budgeted cost of work, (iv) scope change, and (v) productivity.

This study adopted a four-step procedure to construct and simulate the model:

1) Causal loop diagrams: Describing major feedback loops in construction system
2) Stock-flow diagrams: Converting causal loop diagrams into a stock-flow diagram
3) Model validation: Validating the model following typical model testing rules
4) Base run simulation: Analyzing management strategies

Eighty-five essential variables (0) that significantly influence the behavior of the system are identified and included in the model. Based on these identified variables, the system is described by means of a causal-loop diagram. Afterwards, a stock-flow diagram is formulated on the basis of formulated equations and computer code. This allows simulating the model and conducting quantitative analysis. In the model validation research activity, the proposed model goes through a series of tests to build up confidence in it. Finally, the validated model is used to assess the effects of management strategies for C&D waste reduction.

The model consists of the assembly of six subsystems: Construction, Scope change, Productivity, Procurement, Waste, and Earned value subsystems. Design process is not considered in the model scope because in the D-B-B process, design is complete before the start of the construction process. All of these subsystems have the following functions:

- Construction subsystem describes the scheduled physical progress of the project
- Scope change subsystem accounts for additional quantity of work due to change
- Procurement subsystem simulates requirement of materials, stock quantity, and productive material based on the construction and change quantities of work
- Productivity describes the effects of factors on the progress of work
- Earned Value subsystem works out budgeted cost of work progress, schedule performance index, time of completion, and earned schedule at each simulation step and forecasts the global delay and the final delivery date
- Waste subsystem forecasts the probable reduction of construction waste at source due to implementation of BIM process

From these estimates management can evaluate the optimal solution that minimizes duration, cost, and waste. Quality and productivity are maximized by coordinated BIM design process through conflicts and errors detections before the start of the construction process.

4.4.1 Description of the proposed system using causal-loop diagrams

A causal loop conceptually reveals the dynamic process in which the chain effects of a cause are traced through a set of related variables back to the original cause. This conceptual model in a causal loop diagram, as shown in Figure 4-3, is comprised of eight major feedback loops. Out of these seven feedbacks, four are positive (i.e. R1, R2, R3 and R4) and the other four are negative (i.e. B1, B2, B3, and B4). The behavior of the entire waste management system is defined through the dynamic interactions between these feedback loops.

Loop B1 shows the dynamic behavior of schedule management. It can be noted that a longer estimated completion date allows project managers to set a longer revised schedule, which, in turn, smoothens the work schedule progress curve, the schedule value and the schedule performance index (SPI). During the initial three to four month time frame, a new finish date is estimated. This will consequently be earlier than the previous one. In the next step, the new completion date will have a longer estimation again, and so on. Apparently, if time is considered a primary requirement of the project, it will engender a schedule oscillation. This will in turn generate instability on the project such as fluctuations in resource usage, procurement and performance. Moreover, it could take several months to stabilize the project in the equilibrium status.

Such unstable behavior can be avoided by finding proper balance in scheduling completion time. This task may be quite difficult. Firstly, uncertainty of the project may be affected by changes; and secondly, unexpected and unintended side effects may result due to this schedule planning and control.

The positive feedback loop R1 shows one of the side feedback effects for scheduling process of reducing the balancing effect of loop B1 to stabilize schedule oscillations. It reinforces and emphasizes errors in oversized or undersized time estimations. More precisely, a longer estimated completion date makes a greater estimated delay and an increase in work pressure,
which in turn makes the work quality and the work rate decrease. This ultimately results in a weaker SPI and a longer estimated duration. This, in turn, decreases the work quality and the work rate also decreases.

Figure 4-3: Causal loop diagram of waste management at source

Increased schedule pressure produces another balancing feedback loop B2, which helps the first loop to control schedule overruns. Schedule pressure, with a short delay, produces a lower productivity due to overwork and stress on human resources with increase in resource
waste. Thus, it requires more resources to keep the work performed (WP) in line with the schedule. The new additional resources allow a better SPI and a reduced estimated date of completion.

The feedback loop R2 describes that a greater commitment to minimize waste in the project planning phase will encourage the implementation of the latest project management tools and techniques. This, in turn, will allow involving project team members in the design process. A coordinated design process solves most of the constructability issues in the initial stage of the project, resulting in minimization of construction waste. For example, major conflicts among structural and MEP systems could be resolved with a coordinated BIM process right during the design phase. This would lead to more willingness for waste reduction at source.

Feedback loop R3 describes the interrelationships between coordination among the AEC and the construction waste. On one hand, a coordinated design process decreases possible design changes during the construction process and thus decreases waste. On the other hand, it encourages the management to adopt the BIM process for other project activities also.

The process of negative feedback loop B3 is similar to the feedback loop R2 and R3. The difference lies in the addition of variable complexity. If there is more involvement of the AEC team, design quality improves. This decreases the complexity in construction, reducing construction changes. Subsequently, these efforts will contribute to reduction of construction waste.

The balancing loop B4 is formed by adding the variable ‘budgeted cost of work scheduled remaining’ because of the addition of extra work due to change in scope during a construction process. An increase in quantities of work will mean more work to be performed, thereby adversely affecting the construction progress rate.

Reinforcing loop R4 describes an increase in construction complexity as a result of construction overlaps due to an unrealistic estimation of completion date. Increased construction overlaps force changes to the construction schedule and increases in the time of completion.

4.4.2 Model formulation through stock-flow diagrams

After identifying the major variables affecting the construction system, their interrelationships is defined and quantified mathematically. The conceptual model in Figure 4-3 is then converted into a stock-flow diagram by using the STELLA software (STELLA
v9.1.4, 2010) described in the sections below. Many essential details are added through the converting process to the conceptual model to enable simulation quantitatively. For more clarity, detailed description and the units of the all quoted variables in the model are tabulated in Appendix-B.

4.4.3 Variable quantification

Prior to performing quantitative simulation and analysis, quantification of all the variables has been accomplished by collecting data from the real case study of the construction projects in Canada, as described in the methodology in section 1.5. The categories of variables are defined in section 2.4.4.1.

Values of quantitative variables were obtained through the Building Information Model of the project and by referring to the records and the information of the project under study. In a BIM process, quantitative analysis involves measuring the amount of something in the project model and often combining it with other information. Values of quantity takeoff, cost estimate, floor area, space, volume, and parametric and other interpretive values are not visual in nature, but can often be represented in a spreadsheet or database format.

Values of qualitative variables were obtained through surveys, such as questionnaires, interviews, on-site visits, etc. In a BIM process, qualitative analysis considers the nature of the issues, often irrespective of the quantities associated with it. The list of such processes is primarily visual in nature, for example, constructability analysis, system coordination, clash detection, energy analysis, etc. Some variable values were obtained through sequential analysis of the BIM model that included time, both in duration and sequence, for example construction schedule, assembly, and installation sequences.

4.4.3.1 Factors affect productivity subsystem

When constructors price an activity, they estimate the cumulative productivity based on the broad conditions under which the work will be carried out. Thus, their interest primarily is in the cumulative average productivity value, which will be applied throughout the activity (Thomas et al., 1990). The meaning of the term “productivity” varies with its application to different areas of the construction industry (The Business Round Table, 1982). Definitions range from industry-wide economic parameters to the measurement of ‘crews’ and individuals. Each of these measurements has its own unique purpose.

The Department of Commerce, Congress, and other governmental agencies use a Total
Factor Productivity (TFT) model, which is an ‘Economic Model’ to define productivity (Thomas et al., 1990). For the purpose of this study, the TFP model is used to define productivity in the following form (Equation 4-1):

\[
\text{Productivity} = \frac{\text{Total Output}}{\text{Labour} + \text{Materials} + \text{Equipment} + \text{Energy} + \text{Capital}}
\]  

(Equation 4-1)

In this study ‘(Labour + material + equipment + Energy + capital)’ is defined as ‘crew’ (see 2.2.5, RSMeans), and the gross productivity is currently defined as (Equation 4-2):

\[
\text{Gross Productivity} = \frac{\text{Total Output}}{\text{Crew}}
\]  

(Equation 4-2)

If there is a change in scope of the work, the productivity is considered to decrease due to the factors (Figure 4-4): limited work-space available, effect of delivery of material, effect of schedule pressure, and effect of overtime (Whiteside J.D., 2006; Pena-More F. and Park M., 2001; Lemon K.D., 1991; Hout J.C., 1981). Literature survey and the field observations identified the above four factors as the main contributors to affect the productivity in case of any change in scope of work during the construction progress.

**Crew concept:**

‘Crew’ is used to estimate the labour and equipment required for installation to accomplish a particular quantity of ‘item of work’. In the crew concept, cost of total labour hours and equipment is calculated based on current market rates for the installation of unit quantity of work to be accomplished instead of counting man-hours. Total labour hours include exact number of skilled, semi-skilled and unskilled workers and the equipment needed to complete the work (for example: workers and equipment required to carry out one cubic meter of concrete work). Use of crew in the analysis of any construction process provides exact hours of skilled, semi-skilled and unskilled workers, and the hours of equipment required. With this data, current cost per labour-hour is calculated inclusive of cost of tool and plants. This gives the productivity of the work as labour-hour required for daily output:
Based on daily output value, productivity rate is calculated in terms of ‘Labour-hour/crew/day’.

In the above example, Crew C14C for concrete is demonstrated (RCD, 2013). It gives more accurate estimates as the project progresses. But, it can be used at almost any stage of the project. Use of crew concept provides labour hours for all level of skilled workers with the detailed equipment hours, while simple man-hour do not consider separate hours for the different level skills involved and without any consideration of tools and plants.

**Apparent productivity:**

Work progress is affected due to the lack of material at site. The delivery of material affects productivity by changing the ratio of material on site to material needed. Schedule pressure effect varies with the value of ratio of forecast to schedule completion date. Similarly, effect of overtime on construction is a table that varies between zero and one according to the ratio of overtime hours to normal hours per week.
The apparent productivity in construction is defined by the equation composed of ‘gross labour productivity’ and four endogenous variables:

Apparent productivity = (gross labour productivity) * (factors effect productivity)

Factors effect productivity =
(effect of delivery of material) * (effect of overtime) * (schedule pressure effect) * (impact of work space limitation)
Where, ‘Gross labour productivity’ is a constant and considered as ‘tasks performed per crew day’ from the RSMeans database for each item of work. For example, concrete gross productivity = 26.75 m$^3$/crew-day (RSMeans, 2011).

Parameters involved in the ‘apparent productivity’ are described as follows:

(a) Impact of work space limitation:

Productivity is affected by the presence of too many workers in a particular work area. Field observations were conducted to assess the work space required to perform a task for a specific crew size (for example, in case of space required to accommodate one crew for concrete laying to extend the floor for room size expansion). Field observations showed that the productivity decreases if the area available per crew is less than 50 m$^2$.

The graph in Figure 4-5 is prepared based on field observations and discussions with construction managers:

![Graph showing impact of work space limitation](image)

**Figure 4-5: Impact of work space limitation**

The relation below defines the impact of crew size working in a specific area of work. It was observed that in general, for average sized crew and the work to be performed in the confined area, productivity starts reducing if working area per crew is less than 50 m$^2$ area:

Impact of work space limitation = GRAPH (work space per crew available) (5.00, 0.65), (10.0, 0.68), (15.0, 0.7), (20.0, 0.76), (25.0, 0.8), (30.0, 0.93), (35.0, 0.95), (40.0, 0.97), (45.0, 0.98), (50.0, 0.99)
The ratio of work space available per crew is defined by the available area to work divided by the total number of crew required in that work area. The total crew required for specific time period is derived from ‘scope change subsystems’.

(b) Effect of delivery of material:
Progress of work is affected by the lack of material at site and required flow of material is needed. As noted from the field observations and the records, ‘Effect of delivery of material’ varies according to the ratio of ‘material on site to material needed’, between zero and one (Figure 4-6):

![Figure 4-6: Effect of delivery of materials](image)

Productivity is expected to reduce if stock of material at site goes below the targeted quantity of materials as decided by the manager:

Effect of delivery of material = GRAPH (ratio of material on site to material needed)
(0.00, 0.00), (0.2, 0.58), (0.4, 0.7), (0.6, 0.83), (0.8, 0.93), (1.00, 1.00)

(c) Effect of overtime:
As per the literature, when work-time is extended for smaller duration, progress rate is improved but with longer duration, progress rate decreases (Figure 4-7). The loss in productivity applies to total man-hours and not to the overtime man-hours. The following numbers were obtained through on site observations and interviews:
Figure 4-7: Effect of overtime

Productivity is affected considerably when overtime hours increase over 50% of the normal working hours:

\[
\text{Effect of overtime} = \text{GRAPH} \left( \frac{\text{ratio overtime hours to normal hours per week}}{\text{normal hours per week}}, \frac{\text{normal hours per week} + \text{overtime hours}}{\text{normal hours per week}} \right) \times (0.00, 1.00), (0.2, 0.9), (0.4, 0.83), (0.6, 0.75), (0.8, 0.68)\]

(d) Schedule pressure effect:

It has been observed through field study that ‘effect of schedule pressure’ varies with the ratio of forecast to schedule completion date. When there is enough time to completion, schedule pressure will have a negative effect, otherwise it will have positive effect on productivity. The following numbers were obtained by observing the construction schedule and daily work preferences in the observed project (Figure 4-8):
Figure 4-8: Schedule pressure effect

The following trend has been observed during the field studies. Productivity is least affected by schedule pressure in the case of minimum difference between the forecast and scheduled completion date:

\[
\text{Schedule pressure effect} = \text{GRAPH} \left( \frac{\text{forecast completion date}}{\text{schedule completion date}} \right) (0.00, 0.4), (0.25, 0.5), (0.5, 0.6), (0.75, 0.8), (1.00, 0.9), (1.25, 1.00), (1.50, 1.20), (1.75, 0.9), (2.00, 0.6)
\]

4.4.3.2 Schedule Increase subsystem

The module in Figure 4-9 represents the process of projection of revised schedule completion date. The projection is based on the addition of quantity of work due to a change in the scope of work and construction work rate as determined by apparent productivity and the period for which number of crew is engaged.

Schedule increase is addition of time to schedule and is dependent on the rate of progress of additional work:

\[
\text{Increase in schedule} = (\text{adjustment to change}) \times (\text{adjustment fraction})
\]
Here, this additional work is ‘adjustment to change’, which is dependent on the time required to adjust changes due to redesign, error, and the fraction of change in scope of work:

\[
\text{Change monitoring} = \frac{\text{error recover} + \text{fraction concrete change} + \text{redesign}}{\text{concrete apparent productivity}}
\]

\[
\text{adjustment to change} = \frac{\text{change monitoring}}{\text{concrete crew}}
\]

The addition of time to schedule depends on the progress of fraction of work decided to be carried out by the constant ‘adjustment fraction’. An increase in the originally planned schedule affects the overall progress rate of the project.

### 4.4.3.3 Work progress subsystem

This subsystem is illustrated in Figure 4-11. In D-B-B construction projects, construction starts after the completion of the design process with specification of items of work and cost estimates. The contractor starts his workforce planning based on the schedule created from the quantities in the BIM model linked to the crew required and work-month. Productivity is considered to vary with the type of ‘item of work’ and is adopted from the RSMeans data base. The construction progress is calculated as total crew multiplied by labour productivity and planned construction fraction. Simulated BCWP is obtained as work progress multiplied by the estimated cost.

Total work scheduled and the monthly planned progress are obtained from the architectural BIM and its objects linked to the scheduling tool (e.g., MSProject) respectively. For example,
initial concrete work scheduled in this case study was 7977 m³ and planned quantity of concrete executed in the third month was 517 m³ and in the 17th month was 380 m³ (Figure 4-10):

Initial Concrete = 7977 m³

Concrete planned progress = GRAPH(TIME)(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 517), (4.00, 333), (5.00, 526), (6.00, 526), (7.00, 636), (8.00, 569), (9.00, 569), (10.0, 723), (11.0, 723), (12.0, 687), (13.0, 175), (14.0, 651), (15.0, 480), (16.0, 480), (17.0, 380), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00)

Figure 4-10: Concrete planned progress

As work progresses, quantity of work performed decreases with time from the initial work.

Concrete(t) = Concrete(t - dt) + (- concrete progress rate) * dt
Progress rate of the work is derived by the equation, which is the product of productivity and the crew hours engaged. This is further multiplied by the fraction, which accounts for the schedule increase:

\[
\text{Progress rate} = \text{(labour productivity)} \times \text{(crew month)} \times (\text{Schedule Increase})
\]

Crew-day required to perform the planned quantity of work is worked out by the simulation process with the relation:

\[
\text{Crew month} = \frac{\text{(planned progress)}}{\text{(labour productivity)}}
\]

Labour productivity is a constant and is adopted from the RSMeans database (e.g. concrete productivity). The budgeted cost of work progress is simulated with time, by multiplying cost of item-of-work with the quantity of work progressed during that time period. For example, cost of concrete was considered as $750/m³

\[
\text{Concrete labour productivity} = 26.75 \text{ m}^3/\text{crew-day}
\]

\[
\text{BCWP-Concrete} = (\text{WP-Concrete}) \times 750
\]
4.4.3.4 Scope change subsystem

A revised schedule of quantities is calculated through the changes in design incorporated in the BIM model. Fraction of construction work planned by the manager is based on the work available and parallel activities to be carried out. Effects of schedule change, overtime, and material availability are considered to calculate the progress rate. This additional quantity of work is generally carried out for additional cost. Thus, additional simulated WP is obtained to get the final estimated cost of total work (Figure 4-12).

![Figure 4-12: Scope change subsystem](image)

If any change in scope of work occurs during the construction progress, fraction of changed quantity is obtained from the scheduling tool linked to the modified BIM. For example, in the present case study, the fraction change for concrete work was scheduled in the 9th, 10th, and 11th months as 100 m$^3$, 100 m$^3$ and 68 m$^3$ respectively (Figure 4-13), out of total additional concrete work of 268 m$^3$:

Initial (Total concrete change) = 268 m$^3$
Construction productivity is affected by the factors described in apparent productivity subsystem. The progress rate is also subjected to the delays in resuming the construction work due to interruption. The construction manager decides the crew number to be engaged depending on the progress required. Additional construction progress rate is derived by the equation:

\[
\text{Additional construction progress rate} = (\text{apparent productivity}) \times \frac{\text{crew}}{\text{delay}}
\]

Simulated monthly work progress of an additional quantity of work is derived from the equation given below, in which the cost of added work is obtained separately, normally through fresh quotations from the sub-contractors:

\[
\text{Additional Work Progress} = (\text{Additional work}) \times 1000
\]

Where, $1000/m^3$ is the cost of concrete work obtained in the present case study through fresh quotations, against the original cost of $750/m^3$. 

Figure 4-13: Change in scope of work
4.4.3.5 Material subsystem

The maximum inventory level is set by the manager based on the monthly construction progress rate, material required per task, and the extra stock of material at site, to maintain expected material consumption for one month. The process involves time delays due to material procurement and inventory adjustment time. Sometimes, there are delays in material arrivals at site because of long lead times required to transport and inspect them. The materials are classified as productive and waste materials. The effectiveness of material usage depends on the control of waste materials at source (Figure 4-14).

The amount of material in inventory depends on the desired maximum inventory level, material required, and its consumption per task. Material adjustments are made based on financial information and the material in inventory.

\[
\text{Material delivery rate} = \frac{\text{(max material inventory level} - \text{material in inventory})}{\text{(material delivery delay time}}} + \text{(material consumption rate)} + \text{(material wastage rate)}
\]

Sometimes materials are delayed and do not arrive in time, when required. Delays are due to time required for transportation and inspection. Thus the manager sets the level of surplus material in order to maintain a material inventory level that can cover expected material consumption for the desired duration:

\[
\text{Max concrete inventory level} = \text{(concrete required per task} \times \text{concrete required}) \times \text{(surplus concrete order)}
\]

In this case study, for example, the manager set the surplus quantity of concrete as 10% more than required:

\[
\text{Concrete required per task} = 1.1
\]

The total quantity of materials required is periodically obtained through the construction subsystem and the scope change subsystem:

\[
\text{Material required} = \text{(construction progress rate} + \text{(additional construction progress rate)}
\]
Fraction of expected material waste is also taken into consideration while deciding the material inventory level:

Concrete consumption rate = Concrete in inventory * (1 - concrete waste factor)

Material waste is derived by considering the waste factor and waste reduction rate. The default waste factor accounts for the proportion of component that ends up as waste during the construction and/or installation process. The waste reduction rate is a variable, which is derived from the analysis of various factors of the BIM process.

Material wastage rate = (material in inventory) * (material waste factor) * (waste reduction rate)

It was concluded through records and information of the project under study, field observations, and BIM analysis that the waste reduction rate varies between zero and one, according to the efforts to reduce waste (Figure 4-15). The value of efforts to reduce waste ranges from 0 to 100:
The maximum advantage of waste reduction was achieved when an effort of 60 was applied on a scale of 0 as minimum and 100 as maximum:

Waste reduction rate = GRAPH (efforts to reduce waste) (0.00, 0.05), (10.0, 0.09), (20.0, 0.25), (30.0, 0.4), (40.0, 0.45), (50.0, 0.55), (60.0, 0.65), (70.0, 0.55), (80.0, 0.45), (90.0, 0.35), (100, 0.2)

An average material procurement time was decided as one month by the construction manager in the current research project:

Material procurement time = 1 month

4.4.3.6 Waste reduction at source

The study demonstrated that critical categories such as design change and/or error, defective work and rework, and poor coordination, contributes to considerable waste in a construction project. The waste management subsystem aims to reduce potential waste at source at the earliest stages of the construction process (Figure 4-16). This subsystem explains the dynamics and interdependences of the major variables within a construction project. The variables involved in this feedback loop are: effects of implementing BIM technology, involvement of AEC on complexity and constructability, conflict detections during the design process, and their potential effects on frequency of design changes. An organization’s commitment to reduce waste in the early design phase through implementation of modern methods of design (MMD) and construction results in improvements of management capacity.
to coordinate design process and change in traditional construction culture:

Change in use of traditional design coordination methods = Commitment to Implement BIM in early design phase

This in turn will increase the level of application of MMD like BIM. It is observed that maximum benefits rate of waste reduction are achieved during the middle 1/3rd of the project progress due to cumulative effects, though the BIM coordination is performed during its design phase. Hence, commitment to reduce waste is assumed to follow s-shaped growth with increase in waste reduction rate (Figure 4-17):
Figure 4-16: Waste reduction subsystem
BIM study of conflict detection among HVAC and structural components showed that the maximum advantage of BIM in waste reduction at source could be achieved when implemented during the design phase of a construction project:

Commitment to Implement BIM in early design phase = $GRAPH (waste reduction rate) = (0.00, 0.00), (0.1, 0.2), (0.2, 0.475), (0.3, 1.08), (0.4, 2.08), (0.5, 3.45), (0.6, 4.30), (0.7, 4.67), (0.8, 4.88), (0.9, 4.95), (1, 5.00)$

‘Impact of BIM technology on constructability’ is defined by ‘influence on constructability’ which is the ratio of:

$\text{(Construction engineer involvement in design)} / \text{(Level of design complexity)}$

‘Application of Constructability during design process’ is measured on a Likert scale of 0 to 100 in increments of 10%. The impact of constructability on waste reduction varies between zero and one and increases with the increased involvement of a construction engineer in the BIM design process (Figure 4-18):
Figure 4-18: Impact of constructability

Involvement of a construction engineer in the BIM analysis during the design phase was found to be the most effective way to resolve constructability issues and thus reduce waste during construction. It was observed during construction that involvement of construction engineers in design meant coordination was at maximum until the construction of structural components and the installation of some portion of HVAC system:

Impact of constructability on waste reduction = \text{GRAPH (Application of Constructability during design process)} (0.00, 0.00), (10.0, 0.185), (20.0, 0.405), (30.0, 0.515), (40.0, 0.695), (50.0, 0.795), (60.0, 0.89), (70.0, 0.9), (80.0, 0.9), (90.0, 0.915), (100, 0.9)

The level of complexity of design is assumed to vary between zero and one according to the involvement of the AEC in the BIM design process. Complexity decreased with the increased coordination among AEC and the construction engineer. The initial level of design complexity was defined from the BIM model on a Likert scale (Mitchell W.J., 2005) of zero to five, with zero as least complex design:

Level of design complexity \( t \) = \text{Level of design complexity} \( t - dt \) + (- decreasing complexity) \* dt

Initial Level of design complexity = 3

(Decreasing complexity) = (Coordination among AEC)
\[(\text{Construction change}) = (\text{Design change}) / 3\]

Based on the literature study, the frequency of design changes was assumed to reduce with the decrease of design complexity. Decrease in design change varies between zero and three with an increment of 0.5 (Figure 4-19):

<table>
<thead>
<tr>
<th>Level of design complexity</th>
<th>Decreasing design changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2.00</td>
<td>1.50</td>
</tr>
<tr>
<td>3.00</td>
<td>2.00</td>
</tr>
<tr>
<td>4.00</td>
<td>2.50</td>
</tr>
<tr>
<td>5.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

Figure 4-19: Level of design complexity

It was assumed that design changes decrease with the decrease in design complexity:

\[(\text{Decreasing design changes}) = \text{GRAPH (Level of design complexity)} \quad (0.00, 0.5), (1.00, 1.00), (2.00, 1.50), (3.00, 2.00), (4.00, 2.50), (5.00, 3.00)\]

The clash detection process among the structural components and HVAC system stipulated that an average of five conflicts occur per 1000 m² of the floor area, per month of scheduled construction time period (Figure 4-20):
The scale below provides an average value within the limit of 1000 m² floor area for simulation purposes:

Clash detection rate = GRAPH (floor area constructed per month) (100, 0.00), (200, 0.5), (300, 1.00), (400, 1.50), (500, 2.00), (600, 2.50), (700, 3.00), (800, 3.50), (900, 4.00), (1000, 5.00)

Waste reduction rate is a fraction that varied between 0 and 0.65 according to the total efforts made to reduce waste (Figure 4-21):
Based on the literature, field observations, and BIM clash detections, it was concluded that reduction of waste at source varied up to 65% of the generated wastes, most of which was due to dismantling of the constructed work or the rework:

\[
\text{Waste reduction rate} = \text{GRAPH} (\text{efforts to reduce waste}) \ (0.00, 0.05), (10.0, 0.09), (20.0, 0.25), (30.0, 0.4), (40.0, 0.45), (50.0, 0.55), (60.0, 0.65), (70.0, 0.55), (80.0, 0.45), (90.0, 0.35), (100, 0.2)
\]

Effort applied to reduce waste is defined by the relation:

\[
(\text{Efforts to reduce waste}) = (\text{effect of complexity on waste}) + (\text{impacts of conflicts on waste reduction}) + (\text{impact of constructability on waste reduction})
\]

### 4.4.3.7 Earned schedule subsystem

The EVM subsystem uses real data generated during project run time, and it forecasts cost and time performance on the basis of size of scope changes, original scope, schedule and budget, and delay in procurement of new resources (Figure 4-22). The subsystem also describes trends for the future project total actual cost and the completion date.

BCWP is derived from the stocks of WP for all six categories of works performed:
BCWP =
(BCWP Concrete) + (BCWP Earth Work) + (BCWP Finishes) + (BCWP Masonry) +
(BCWP MEP) + (BCWP Steel)

Running the model integrates cost and schedule data over time and compares existing progress to the planned schedule through simulation under different conditions.

The variance in the planned schedule is derived from the relations:

Schedule Variance = BCWP – BCWS

Figure 4-22: Earned Value management subsystem
Budgeted cost of the scheduled work is derived from BIM for initially scheduled time of completion, 25 months (Figure 4-23):

\[
BCWS = \text{GRAPH (TIME)} (0.00, 0.00), (1.00, 356984), (2.00, 713968), (3.00, 1.4e+006), (4.00, 2.5e+006), (5.00, 3.6e+006), (6.00, 5.7e+006), (7.00, 7.9e+006), (8.00, 1e+007), (9.00, 1.3e+007), (10.0, 1.7e+007), (11.0, 2e+007), (12.0, 2.4e+007), (13.0, 2.7e+007), (14.0, 3e+007), (15.0, 3.3e+007), (16.0, 3.6e+007), (17.0, 3.8e+007), (18.0, 4e+007), (19.0, 4.2e+007), (20.0, 4.3e+007), (21.0, 4.3e+007), (22.0, 4.4e+007), (23.0, 4.4e+007), (24.0, 4.4e+007), (25.0, 4.5e+007)
\]

Figure 4-23: Work scheduled

The actual construction cost incurred (ACWP) is derived from:

\[
ACWP = BCWP + \text{(additional Work Progress)}
\]

Schedule Performance Index = IF (BCWP = 0 OR BCWS = 0) THEN 0 ELSE BCWP / BCWS

Earned schedule is derived from the relation:

Earned Schedule = scheduled Progress Months; where

‘Scheduled progress months’ is a table that varies between month 0 and 25 according to the value of budgeted cost of work performed (Figure 4-24):
Scheduled Progress Months = GRAPH (BCWP) (0.00, 0.00), (1.8e+006, 3.33), (3.6e+006, 5.00), (5.4e+006, 5.83), (7.1e+006, 6.67), (8.9e+006, 7.41), (1.1e+007, 8.09), (1.2e+007, 8.68), (1.4e+007, 9.27), (1.6e+007, 9.85), (1.8e+007, 10.4), (2e+007, 10.9), (2.1e+007, 11.4), (2.3e+007, 11.9), (2.5e+007, 12.4), (2.7e+007, 12.9), (2.9e+007, 13.5), (3e+007, 14.0), (3.2e+007, 14.6), (3.4e+007, 15.2), (3.6e+007, 15.9), (3.7e+007, 16.6), (3.9e+007, 17.4), (4.1e+007, 18.6), (4.3e+007, 20.0), (4.5e+007, 25.0)

Based on value of ‘scheduled progress months’, earned schedule is projected for the whole project duration (Figure 4-24).

![Graph of scheduled progress months](image)

**Figure 4-24: Schedule progress months**

Projection of total cost of the project at completion (estimate at completion, EAC) is derived by multiplying cost escalation factor to the total cost of work:

$$EAC = (BCWP + \text{additional Work Progress}) \times \text{cost escalation factor}$$

Cost escalation is proportional to the fraction increase in the scheduled time of completion:

Cost escalation factor = Schedule Increase / (Planned Duration + Schedule Increase)

Additional cost due to change in scope of work is obtained from:

Additional Work Progress =
(WP additional Concrete) + (WP additional finishes) + (WP additional masonry) + (WP additional steel)
The forecast final duration of completion of project is derived from:

\[
\text{Independent Estimate at Completion Time} = \frac{\text{Planned Duration}}{\text{IF} (\text{Schedule Performance Index} = 0) \text{ THEN } 1 \text{ ELSE Schedule Performance Index}}
\]

### 4.4.4 Model simulation

The assembly of the subsystems is shown in Figure 4-25. The computer model of each subsystem created in STELLA is presented in Appendix D.

![Diagram of Stock-flow diagram of dynamic-BIM waste management system](Image)

**Figure 4-25:** Stock-flow diagram of dynamic-BIM waste management system  
(Please see Appendix-D for complete computer model)
4.4.4.1 Model validation

The quantitative analysis was performed by assigning an appropriate value for each variable by collecting data from an actual construction project in Canada. The studied case was a new framed-structure institutional building located in western Canada. The gross floor area of the building was 16250 square meters. The budgeted cost and scheduled time of completion were CDN 44.60 million and 25 months, respectively. The building is a 5 storey; LEED Gold certified building and its construction was started in March 2009.

Data were mainly collected from the BIM model, site survey, and the literature. The site survey consisted of several formal and informal meetings and communication with four on-site staff including one project manager, one construction site manager, and other two professional engineers. Selection of these experts was done based on their high experience in construction management, and including waste management with LEED standards. Data were also collected through interviews and consultation with the concerned architect and design firms, and the consulting engineering firms of similar capacity. The model is set to run during a total period of 25 months. Model equations determined by incorporation of data collected from BIM-model, site, and survey are attached in Appendix A.

The total construction work was distributed into six main items of work: Earth work, concrete, steel, masonry, MEP and finishes. The ‘finishes’ consisted of remaining works including main items of work like flooring, walls, ceiling, doors/windows, painting, etc. The productivity and crew hours required to compute the progress rate of a particular item of work (for example: cubic meter of concrete work) were considered individually based on RSMeans (RCD, 2013). BCWP for the item of work was calculated based on the cost of labour, material, and equipment for that particular year.

The model has been validated by all the necessary tests including (i) the causal loop diagram for modeling waste management at source that corresponds to the statement of the problem, (ii) equations corresponding to the causal loop diagram, (3) dimensional validation of the model, and (4) passing the model through the extreme condition test (by changing variable values to extreme values), and (5) model must go through sensitivity analysis.
Analysis with BIM data

The model was utilized to perform the simulations using the values of the variables obtained through the BIM model of the building to identify its performance in terms of time, cost, and waste. Table 4-1 shows a list of major variables quantified through the BIM model of the project.

Table 4-1: Values of variables obtained through BIM model

<table>
<thead>
<tr>
<th>Variables Quantification through BIM</th>
<th>Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned quantity of work</td>
<td>4-2</td>
</tr>
<tr>
<td>Planned monthly progress</td>
<td>4-3</td>
</tr>
<tr>
<td>Additional quantity of work due to change</td>
<td>4-4</td>
</tr>
<tr>
<td>Planned monthly quantity of additional work</td>
<td>4-5</td>
</tr>
<tr>
<td>Budgeted Cost of Work Scheduled</td>
<td>Appendix A</td>
</tr>
<tr>
<td>Limit of Work Space</td>
<td>Model visualization</td>
</tr>
<tr>
<td>Design changes</td>
<td>70</td>
</tr>
<tr>
<td>Application Level of BIM Technology</td>
<td>67</td>
</tr>
<tr>
<td>Expected Level of Applying BIM Technology</td>
<td>40</td>
</tr>
<tr>
<td>Clash detection</td>
<td>75</td>
</tr>
<tr>
<td>Complexity level</td>
<td>3</td>
</tr>
</tbody>
</table>

During the design coordination, 75 major clashes were detected among structural and HVAC components, which would create 70 major design changes during the construction process. Initially it was decided to use BIM at a level of 40 on scale of 0 to 100. However, simulations confirmed a BIM implementation level of 67 to achieve the predicted waste reduction at source. The design was found to be of moderate complexity level 3.

Planned quantities of work in the pre-construction stage calculated from BIM are listed in Table 4-2:

Table 4-2: Initial planned total quantities of items of work

<table>
<thead>
<tr>
<th>Item of work</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Work</td>
<td>84094 m$^2$</td>
</tr>
<tr>
<td>Concreting work</td>
<td>7977 m$^2$</td>
</tr>
<tr>
<td>Steel work</td>
<td>1380 tonne</td>
</tr>
<tr>
<td>Masonry work</td>
<td>2379 m$^3$</td>
</tr>
<tr>
<td>MEP</td>
<td>16248 m$^2$</td>
</tr>
<tr>
<td>Finishes</td>
<td>16248 m$^2$</td>
</tr>
</tbody>
</table>
The planned quantities of work (earth work, concrete, steel, masonry, MEP, and finishes) and the monthly scheduled progress as taken from the BIM model are shown in Table 4-3. Quantity of item MEP and Finishes were considered as per square metre area of floor area of construction work.

Table 4-3: Planned monthly progress (BIM)

<table>
<thead>
<tr>
<th>Schedule (Months)</th>
<th>EW (m³)</th>
<th>Concrete (m³)</th>
<th>Steel (tonne)</th>
<th>Masonry (m³)</th>
<th>MEP (m²)</th>
<th>Finishes (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>96</td>
<td>608</td>
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<td>154</td>
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<td>98</td>
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<td>17.00</td>
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<td></td>
<td>303</td>
<td>275</td>
<td></td>
</tr>
</tbody>
</table>

Additional quantities resulting from change in scope of work and extracted from the BIM model are given in Table 4-4.

Table 4-4: Change in scope of work

<table>
<thead>
<tr>
<th>Item of work</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>268 m³</td>
</tr>
<tr>
<td>Steel reinforcement</td>
<td>33 tonne</td>
</tr>
<tr>
<td>masonry</td>
<td>15 m³</td>
</tr>
<tr>
<td>Finishes</td>
<td>195 m²</td>
</tr>
</tbody>
</table>
These changes were planned by the construction manager as per the schedule linked to BIM (Table 4-5):

<table>
<thead>
<tr>
<th>Contract Time (Months)</th>
<th>EW (m³)</th>
<th>Concrete (m³)</th>
<th>Steel (tonne)</th>
<th>Masonry (m³)</th>
<th>MEP (m²)</th>
<th>Finishes (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9.00</td>
<td>0</td>
<td>100</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>10.00</td>
<td>0</td>
<td>100</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>11.00</td>
<td>0</td>
<td>68</td>
<td>10</td>
<td>5</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>12.00</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>13.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 4.4.5 Results and discussions

Results obtained from the simulation run with the BIM model integration are discussed in this section to ascertain the validity of the virtual data used to forecast cost, schedule overruns, and the waste reduction at source. The results obtained from three scenarios involve:

(i) Scenario-1: Pre-construction

(ii) Scenario-2: Change in scope of work

(iii) Scenario-3: Waste reduction

Detailed results of each scenario are as described below:

#### 4.4.5.1 Scenario-1: Pre-construction

As the case study consisted of the D-B-B process, all data related to designs, drawings, cost, specifications, and the proposed schedule of work were available prior to the start of construction work. The data were collected from the BIM model, and the SDM model was set to run for a period of 25 months to validate the pre-construction scenario. At this stage, there is no change in scope of work and no BIM efforts have been made to reduce construction waste. The results obtained from the simulation run are given in Table 4-7. The inputs given to the SDM are in Table 4-6.
Table 4-6: Inputs to the SDM model for Scenario-1

<table>
<thead>
<tr>
<th></th>
<th>Schedule of work</th>
<th>Productivity</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Work</td>
<td>Table 4-3</td>
<td>206 m³/crew-day</td>
<td>22.59 $/m³</td>
</tr>
<tr>
<td>Concrete</td>
<td>--</td>
<td>26.75 m³/crew-day</td>
<td>750 $/m³</td>
</tr>
<tr>
<td>Steel</td>
<td>--</td>
<td>10.10 ton/crew-day</td>
<td>3375 $/ton</td>
</tr>
<tr>
<td>Masonry</td>
<td>--</td>
<td>3.8 m³/crew-day</td>
<td>900 $/m³</td>
</tr>
<tr>
<td>MEP</td>
<td>--</td>
<td>10 m²/crew-day</td>
<td>1020 $/m²</td>
</tr>
<tr>
<td>Finishes</td>
<td>--</td>
<td>6 m²/crew-day</td>
<td>825 $/m²</td>
</tr>
</tbody>
</table>

The output obtained is tabulated in Table 4-7:

Table 4-7: Pre-construction scenario output

<table>
<thead>
<tr>
<th>Schedule (Month)</th>
<th>Construction Change ($)</th>
<th>Cost of construction (Million $)</th>
<th>Increase in schedule (Month)</th>
<th>Anticipated waste (tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.36</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.71</td>
<td>0</td>
<td>12.35</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1.43</td>
<td>0</td>
<td>24.70</td>
</tr>
<tr>
<td>4</td>
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<td>37.05</td>
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<td>99.45</td>
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<tr>
<td>8</td>
<td>0</td>
<td>10.44</td>
<td>0</td>
<td>131.16</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>13.48</td>
<td>0</td>
<td>166.60</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>16.51</td>
<td>0</td>
<td>197.92</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>20.08</td>
<td>0</td>
<td>226.07</td>
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<tr>
<td>12</td>
<td>0</td>
<td>23.65</td>
<td>0</td>
<td>254.34</td>
</tr>
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<td>13</td>
<td>0</td>
<td>27.04</td>
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<tr>
<td>14</td>
<td>0</td>
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</tr>
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<td>15</td>
<td>0</td>
<td>33.47</td>
<td>0</td>
<td>333.40</td>
</tr>
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<td>16</td>
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<td>35.97</td>
<td>0</td>
<td>358.19</td>
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<td>17</td>
<td>0</td>
<td>38.47</td>
<td>0</td>
<td>383.50</td>
</tr>
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<td>18</td>
<td>0</td>
<td>40.34</td>
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<td>409.08</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>41.59</td>
<td>0</td>
<td>432.26</td>
</tr>
<tr>
<td>20</td>
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<td>0</td>
<td>450.89</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
<td>43.37</td>
<td>0</td>
<td>467.24</td>
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<tr>
<td>22</td>
<td>0</td>
<td>43.91</td>
<td>0</td>
<td>481.58</td>
</tr>
<tr>
<td>23</td>
<td>0</td>
<td>44.27</td>
<td>0</td>
<td>494.93</td>
</tr>
<tr>
<td>24</td>
<td>0</td>
<td>44.44</td>
<td>0</td>
<td>507.78</td>
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<tr>
<td>Final</td>
<td>0</td>
<td>44.62</td>
<td>0</td>
<td>520.38</td>
</tr>
</tbody>
</table>

When there is no change in construction work during the entire construction process, cost remains the same as estimated (44.60 million dollars) with no increase in time of completion of work. An anticipated amount of waste generated equal to 520.38 tonnes is derived through the simulation process without implementing any BIM technology during the design phase. All these values are very close to the actual quantities (Table 4-8).
Table 4-8: Comparison of Pre-construction data with simulation run

<table>
<thead>
<tr>
<th></th>
<th>Actual</th>
<th>Simulated base run</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time of completion</strong></td>
<td>25 month</td>
<td>25 month</td>
</tr>
<tr>
<td><strong>EV (ACWP)</strong></td>
<td>$44.60 million</td>
<td>$44.62 million</td>
</tr>
</tbody>
</table>

The graph in Figure 4-26 shows that schedule performance index is one for the whole period of construction:

![Graph showing schedule performance index](image)

**Figure 4-26: SPI (t) for Scenario-1**

Independent estimate at completion (time) also remains stable at 25 months for the whole period of construction (Figure 4-27):
4.4.5.2 Scenario-2: Change in scope of work

A change in scope of work was initiated by the owner in the 9th month during the construction progress (Table 4-5). The BIM model was revised accordingly with these changes and the quantities were input to the SDM model to observe the effects of change in scope of work.

The model is set to run for a total period of 30 months. Data collected from the BIM model were incorporated into the SDM model along with data collected from site and the literature. The model equations determined are attached as Appendix-A.

Based on the real project data, the construction change simulation run shows that the building project consumes 6312.58 crew-months, finishes in 31.32 months, and costs CDN 48.18 million. The model’s output is quantitatively quite close to the actual data as shown in Table 4-9.

| Table 4-9: Comparison of historical and simulated run results after construction change |
|-----------------------------------------------|--------------|---------------|
| Time of completion                            | Actual       | Simulated base run | Deviation (%) |
|                                               | 30 month     | 31.32 month     | + 1.044       |
| EV (ACWP)                                     | $ 47.60 million | $ 48.18 million | + 1.015       |
| Total Waste                                   | 529.95 tonne | 507.33 tonne    | - 4.268       |
The waste projected in this simulation run does not consider application of the coordinated BIM process during the design phase (Table 4-10). The detailed analysis of the simulation run results in the present scenario described below:

<table>
<thead>
<tr>
<th>Schedule (Month)</th>
<th>Concrete Actual</th>
<th>Concrete Simulated</th>
<th>Steel Actual</th>
<th>Steel Simulated</th>
<th>Mixed Actual</th>
<th>Mixed Simulated</th>
<th>Total Actual</th>
<th>Total Simulated</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.00</td>
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<td>7.90</td>
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<td>0.00</td>
<td>0.86</td>
<td>0.00</td>
<td>10.69</td>
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<td>24.70</td>
<td>16.17</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.86</td>
<td>0.00</td>
<td>21.64</td>
<td>37.05</td>
<td>22.50</td>
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<tr>
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<td>0.86</td>
<td>0.00</td>
<td>27.93</td>
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<td>28.79</td>
<td>49.40</td>
</tr>
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<td>61.75</td>
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<td>122.16</td>
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<td>152.63</td>
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<td>223.37</td>
</tr>
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<td>225.61</td>
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</tr>
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<td>25.66</td>
<td>35.18</td>
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<td>281.60</td>
<td>335.87</td>
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<td>74.93</td>
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<td>38.10</td>
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<td>209.95</td>
<td>304.94</td>
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</tr>
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<td>296.40</td>
<td>441.49</td>
<td>494.62</td>
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<td>308.75</td>
<td>489.80</td>
<td>507.16</td>
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<td>43.55</td>
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<td>502.68</td>
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<td>43.55</td>
<td>46.61</td>
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<td>308.75</td>
<td>516.87</td>
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<td>46.62</td>
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<td>308.75</td>
<td>526.09</td>
<td>507.32</td>
</tr>
<tr>
<td>30</td>
<td>0.00</td>
<td>104.20</td>
<td>46.78</td>
<td>46.63</td>
<td>352.50</td>
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</tr>
<tr>
<td>31</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>529.95</td>
<td>507.33</td>
<td></td>
</tr>
</tbody>
</table>

The model simulation result shows that construction progress experienced a significant amount of cost overrun due to change in scope of work. This is close to the actual cost overrun of $3.0 million. Expectation of total project cost against budgeted cost of work scheduled is shown in Figure 4-28. EAC in this simulation represents the cost currently to be incurred to complete the project. Curve 1 shows the amount of scheduled progress and is planned to reach completion at the 25th month. Until the 5th month, progress is fairly good as
planned but starts lagging from the start of the 9\textsuperscript{th} month after change in scope of work. This is due to the decrease in gross productivity and delays in material availability at site. Work progress goes up after measures are taken to provide the extra labour and material resources. The manager determines the additional construction progress rate with respect to expected delays. For example, in this case study a fraction delay (f\text{delay}) of 0.5 for concrete was assumed depending on the availability. The forecast for completion date was projected as 31.32 months against 25 months and a total cost of $48.18 million (curve 2) against estimated cost of $44.6 million.

![Figure 4-28: Expected cost at completion of work](image)

Work space limitation is one of the major factors that affected the construction productivity. A balance of productivity and progress was maintained by allowing appropriate crew numbers at the construction change area. This was achieved by analyzing the work space availability through the BIM model. The ratio of forecast to schedule completion date (Figure 4-8) was monitored by projecting IEAC(time) from schedule increase. This suggested the required progress rate to complete the work within the revised schedule. In the present case study the highest schedule pressure observed was one. An increase in the effect of schedule pressure on productivity was observed at the start of the 6\textsuperscript{th} month, which continued until the 14\textsuperscript{th} month with cumulative effect until the end of the 30\textsuperscript{th} month (Figure 4-29).
Figure 4-29: Effect of schedule pressure on productivity

An increase in scheduled time was observed from the 9th month to the 20th month of the construction progress (Figure 4-30).

Figure 4-30: Increase in scheduled completion date

Estimated cost at the completion date is derived by multiplying a factor for cost escalation to the sum of BCWP and additional cost of change in scope of work:

\[(\text{BCWP} + \text{additional Work Progress}) \times \text{(cost escalation factor)}\]

The cost escalation factor varies with the ratio of schedule increase to projected time of completion of work (Figure 4-31). In the present case study, this factor varies up to a
maximum value of 0.10.

Figure 4-31: Cost escalation factor

Schedule increase is accumulated in the stock by flow of ‘addition to schedule’ and is projected by multiplying ‘change adjustment’ with a factor. This factor is to adjust the increasing completion date, and is decided by the construction manager by increasing the crew number at work. In the present scenario, a factor of 0.115 was considered to control the schedule increase within a limit of 3 months. A requirement of a total of 6312 crew-month was projected against 5801 crew-month originally planned.

The simulation showed that if no measures had been taken to correct the schedule completion date, then the Earned Schedule would have achieved a value of 21.05 months in a 30 month period of construction (Figure 4-32).
The simulation showed a steep increase in completion date up to a maximum of 31 months (Figure 4-33) while the per-construction simulation stabilized at a constant value of 25 months after an initial increase (Figure 4-27).

Change in scope of work introduced a decrease in schedule performance, which is shown on the graph for SPI(t) in Figure 4-34.
The simulation graph shows a steep decline in SPI(t) from the 9th month when the change scope of work was introduced into the construction process. This can be verified by comparing the simulated graph created from the pre-construction simulation (Figure 4-26). It shows a constant SPI(t) as one after the 4th month, when the construction process became stable after the initial setup.

4.4.5.3 Waste reduction scenario

This study clearly indicated that commitment to minimize waste in the project planning stage could be a major factor influencing waste generation at source. Application of modern designing techniques such as BIM and coordinated design efforts could greatly reduce the waste at source. Results showed that lack of coordination among design and construction engineers during the design phase could result in numerous conflicts among structural and mechanical components of the building. This was found to be one of the major factors contributing to construction waste. Though change in scope of work during the construction process could be one of the factors, it was not found to be the major reason for construction waste production. Table 4-11 shows the potential waste that could be reduced at source with early design coordination.
The BIM process could identify 75 major clashes during the model analysis that were the prime cause for project delay and waste production. There is an increase in cost due to increase quantities of items of work with change in scope of work. But, decrease in waste generation, though quantity of material use has increased. The simulation process shows that if these conflicts were detected during the design phase, they could have reduced the waste up to the quantities shown in Table 4-12.

<table>
<thead>
<tr>
<th></th>
<th>Actual</th>
<th>Simulated base run</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of completion</td>
<td>30 month</td>
<td>31.32 month</td>
<td>+ 1.044</td>
</tr>
<tr>
<td>EV (ACWP)</td>
<td>$ 47.60 million</td>
<td>$ 48.18 million</td>
<td>+ 1.015</td>
</tr>
<tr>
<td>Total Waste</td>
<td>529.95 tonne</td>
<td>394.77 tonne</td>
<td>- 25.510</td>
</tr>
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</table>

Table 4-11: Waste reduction at source with BIM design coordination
<table>
<thead>
<tr>
<th>Schedule</th>
<th>Concrete</th>
<th>Steel</th>
<th>Mixed</th>
<th>Total</th>
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<td></td>
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<td>Actual</td>
<td>Simulated</td>
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<td>78.87</td>
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<td>31</td>
<td>0.00</td>
<td>79.01</td>
<td>46.78</td>
<td>36.22</td>
</tr>
</tbody>
</table>
Figure 4-35 shows the pattern of potential waste reduction during the construction period of 30 months:

![Graph showing waste reduction pattern](image)

**Figure 4-35: Simulation results of reduced construction waste**

The graph shows a constant waste reduction rate from the 5th month to the 19th month, during which most of the structural and MEP works were completed. Waste production stopped from the 26th month, when mainly finish works were executed.

### 4.4.6 Model validation and sensitivity analysis

Sensitivity analysis allows determining the accuracy level of parameter values and validity of the model. It also allows experimenting with a wide range of values to understand the behavior of a system in extreme situations.

Sometimes, an extensive sensitivity analysis is not possible, especially in case of a large model. Thus, most uncertain and influential parameters on the behavior of the model are only used to perform the sensitivity analysis.

The parameters and the initial values of stock used to explore the sensitivity and validity of this model are: (1) Total concrete change, (2) concrete crew, (3) overtime, (4) Application level of BIM, (5) Application level of constructability during design process, (6) Level of design complexity, (7) Frequency of design changes, and (8) Frequency of conflicts between building components.

The parameter ‘Total concrete change’ is selected out of six construction sub-system parameters, because it contributes to the major quantity of change in scope of works.
Sequencing of other activities is based on completion of concreting works in most of the sequencing of item of works.

A set of values ranging from zero to maximum for above parameters 1 through 8 was tried to see how cost, time and waste generation varies with time and the way system behaves. Three reasonable values were considered for the analysis:

Total concrete change – 300 m$^3$, 750 m$^3$ and 1200 m$^3$; concrete crew – 4, 5 and 6; overtime – 0 hour, 3 hour and 6 hour; Application level of BIM technology – 0, 25 and 50; Application level of constructability during design process – 0, 250 and 500; Level of design complexity – 0, 2.5 and 5.0; Frequency of design changes – 0, 35, and 70; and Frequency of conflicts between building – 0, 37.5 and 75.

The major parameter to consider for change in scope of work was increased to 15% of the initial quantity of work i.e. 1200 m$^3$ to know the system behavior. The comparative run showed how estimated cost at the completion of work varied with change in scope of work and the crew (Figure 4-36). All the curves within three different scenarios do not look exactly the same but exhibits similar shapes. The parameter changes do not affect the general mode of behavior of the system. All the three curves show an increase in cost following the typical s-shape of progress curve. This demonstrates the fact that higher the change in scope of work, greater is the cost of completion.

1- $52.7$ million; 2- $57.0$; 3- $58.1$; (Concrete = $300-1200$ m$^3$; Crew = 4-6 no.)

![Figure 4-36: Estimate At Completion (Concrete 300-1200 m$^3$)](image)
Further, there was an increase in schedule from 4.95 months to 7.11 months with increase in scope of work with a fixed crew number at work as 4 (Figure 4-37).

<table>
<thead>
<tr>
<th>1 - 4.95 months; 2 – 6.99 months; 3 - 7.11 months</th>
</tr>
</thead>
</table>

Concrete = 300-1200 m³; Crew = 4 no.

**Figure 4-37: Schedule Increase (Concrete 300-1200 m³, crew 4 no.)**

There was a decrease in time with increase in number of crew at work to 6 (Figure 4-38), but this reduced the productivity due to insufficient space available to work at site for increased crew size (Figure 4-39).
1- 4.95 months; 2 – 5.61 months; 3- 4.77 months

Figure 4-38: Schedule Increase (Concrete 300-1200 m³, crew 4-6 no.)

1- 0.61; 2- 0.42; 3- 0.42

Figure 4-39: Factors effect productivity (Concrete 300-1200 m³)

Concrete = 300 – 1200 cum; Crew = 4-6 no.

Figure 4-40 shows the variation in total waste generation with the application level of BIM technology. Curve-1 shows waste created when there is no BIM implementation on the project. Curve-3 shows with BIM implementation at its maximum level of 100.
Concrete = 300 – 1200 cum; Crew = 4-6 no.

**Figure 4-40: Total waste (Concrete 300-1200 m³)**

Behavior of the model was examined under extreme condition by assigning values to specific variables. The generated behavior reflected the real system behavior as anticipated and understood. It can be concluded on the basis of these results that i) BIM data can be reasonably used to examine the behavior of the real life construction system and ii) implementation of BIM early in the design coordination process has significant impact on waste reduction at source. Study demonstrated that among the eight loops described in section 4.4.1, loops R2 and R3 were dominant in terms of waste reduction at source, and loops R1 and B4 were dominant for prediction of cost and time over runs due to change in scope of work.

Following model boundaries and limitations could be defined by conducting the above extreme condition tests:

1) When change in scope of work exceeds 50% of the initial quantity of work, model runs out of the total time period of 30 months, and has to be run for increased simulation run time.

2) Model simulations are performed in the units of one month as minimum time for simulation.

3) Model can define the items of work into five broadly defined modules as earth work,
concrete, steel work, brick work, MEP and finishes. All the items, which could not be included, are included into the finishes.

4.4.7 Summary

Minimization of construction waste quantities is of paramount importance for sustainable construction waste management and planning. The construction process is highly dynamic in nature. Optimization of construction waste using real-time information of BIM integrated with a dynamic simulation technique is more realistic than the historical data analysis techniques.

A major quantity of construction waste is created due to rework and poor material management practices. Construction projects often experience time and cost overruns due to changes in scope of work. Changes in design, lack of modular coordination, and poor integration of building systems are the main causes for changes in scope in construction projects. Rework makes material management more complex during the construction process as it immediately attracts a change in material requirement. BIM has a unique capability of instantly generating the bill of material quantities, in real time, for changed design. Such changes in material requirements affect the whole material management system of a project and therefore managers need a decision supporting tool to plan the delivery, distribution, reuse, recycling, and disposing of materials as per the time schedule restrictions.

The study discussed in this section proposed a modelling methodology to address material management dilemmas in the construction process. The model used BIM with a generic SD model to represent and simulate the interactive structure of construction work by considering the dynamic nature of material requirement. Since the proposed model allows users to fine-tune the input variables, it is flexible enough to adjust the model to better reflect the reality according to different conditions.
Chapter 5 : BIM-Partnering Framework for Public Construction Projects

5.1 Overview

BIM has proven to reduce construction waste at source through a coordinated design process. The conflict detection during the design process is one example of avoiding costly, abortive work at the construction stage. It is widely accepted as an essential tool for built environment professionals to improve their productivity from the design to the downstream construction stages. However, industry faces challenges in considering the use of a new technology in their operations.

The construction industry exhibits a low maturity in the use of BIM, since no significant changes in the traditional business model accompany the introduction of new tools (BIM SmartMarket Report, 2009). However, to maximize the benefits of this technology, a variety of organizational, procedural, and technical issues need to be addressed. The survey conducted by McGraw Hill on BIM adoption (BIM SmartMarket Report, 2009), did not warrant enough demand for BIM from clients.

In the public sector, the central issue is moving from a low-bid process to any of the other alternative project delivery methods. As the public sector client is accountable to the public, an open competitive bidding process that awards based only on price is highly preferable. However, selecting a contractor based solely on price greatly diminishes the significance of important criteria such as time and quality, which do not guarantee a maximum value (FHWA, 2012). Lowest bid price as the sole award criterion encourages unqualified contractors to submit bids (Herbsman et al., 1992) with the intent of recovering their losses through change orders and claims (Crowley et al., 1995). Therefore, low bid is not necessarily the ‘best value’ for the owners. “The means of obtaining the ‘best value’ under this system is to award a contract to the responsive and compliant bidder, who is willing to fulfill the terms of the contract for the lowest dollar value with innovative ideas.” (Bedford, 2009)

The Institute for BIM in Canada has suggested that one way to facilitate BIM adoption may be to make BIM a mandatory requirement for public projects (IBC, 2012). Moreover, it has recommended developing supplements to existing contract and procurement documents (Cefrio 2012). The public sector is more focused on administrative decision making, where using BIM is not their first priority but only one of many responsibilities (Cefrio 2012). Thus,
it becomes important to review and evaluate the current performance of the procurement process to ensure that the public sector obtains a greater value for the money in their construction projects. No such methodology, framework, or analysis in public procurement with BIM is available in the published literature. Usage of BIM will certainly increase in the future, especially with its eventual adoption by the public sector, followed by appropriate project delivery methods seeking to make the most efficient use of a collaborative BIM model (Cefrio 2012).

**Results of the questionnaire survey**

As mentioned in Chapter 1 (methodology), industrial data was collected through a questionnaire survey, which focused on the implementation of BIM technology to reduce the design errors through coordinate the BIM design process. Organizations located in major BIM user countries were selected for the survey. Altogether 24 responses were received. Out of the 24 responses, 62% of the organizations were employed 16-25 people, and 42% of the employees were found involved in the design process. The organizations involved mainly with design works were 84%, and the rest were involved with design and construction works. The survey consisted of organizations involved in design and construction of building projects. Nine percent of the total responses were from public construction organizations. D-B-B and D-B were the most used procurement methods, out of which 81% projects were D-B-B. Participants of the survey were drafters, CAD-operators, graduate engineers and the project managers with a minimum 9 to 12 years of experience in the construction industry.

Detailed findings of the survey are as below:

1) Two-third of the organizations have been using BIM for a minority of the projects as a moderate user

![Survey Results](image-url)
2) 20 out of 24 respondents used BIM for the architectural applications

3) Improved coordination among the design teams was the main reason for adopting BIM for 62% of the organizations.

4) Three-fourth of the organizations realized greatest value of BIM in reducing rework

5) Majority of organizations (84%) did not have any procedure to produce error free designs, and realized a need for the development of a coordinated BIM design process for D-B-B.
5.2 Suggested Approach for Public Procurement with BIM

A comprehensive literature review indicated that there is no significant new project delivery methods evolved with BIM integration. Almost all the existing delivery methods are mere modifications or slight variations of past established methods. The traditional method of procurement has been criticized for separating the design and construction processes, which obstructs communication and coordination between design and construction teams. Under the traditional procurement method, design documentation is supposed to be completed before being posted for tender, so as to ascertain cost for the project (PCCBC, 2012). Design-Build and Early Contractor Involvement (ECI) are the notable extensions of design-bid-build in the most recent major improvement projects (FHWA, 2012).

In the proposed Early BIM Partnering (EBP) approach, commitment to BIM is made very early in the project planning phase (Figure 5-1). A fully integrated team is not necessary for effective project delivery to overcome existing organizational and behavioral barriers (Baiden et al., 2006). A coordinated BIM-Partnering framework for the design procurement is proposed with the following interrelated objectives:

1. To provide a structured approach for potential and willing public sector BIM users to understand current BIM capabilities and assess their BIM implementation readiness.

2. To create awareness about BIM applications and their usability in different project activities and phases.

3. To enable public owners to review their existing processes for implementation and utilization of BIM based design collaborations and to identify the likely legal and procedural conflicts that would have arisen among their project stakeholders.

4. To provide a computational framework (Succar, 2009) that can be developed and implemented as an interactive computational BIM-Partnering design management tool to assist BIM managers and similar roles. The data related to the initial framework development was collected from a public sector (institutional) construction project.

Projects of any size have either an internal or external contract manager, who is technically and managerially competent, and to whom all parties report. The reporting parties in the proposed BIM partnering framework are:

1. Owner’s design consultant (also referred to as the “Partnering Architect” or the “BIM Architect”)
2. Contractor and the contractor’s BIM architect/engineer as a member of the Contractor’s organization, who contractually is one among many subcontractors.

Each of these reporting parties (including the Program Manager) is contractually bound to the owner, with the owner’s program manager acting as its representative. The contractor holds the other subcontracts.

![Diagram](image)

**Figure 5-1: Early BIM-partnering delivery method**

Figure 5-2 explains the iterative process of constructing a ‘Full Design Model’ to maintain the target value of the project which is initially obtained in a ‘Substantive cost estimate’ (PWGSC 2012), either through a traditional cost estimation based on 2-dimensional drawings or through model based cost estimation. ‘Substantive Estimate’ (Class ‘B’ estimate) is in elemental cost analysis format and is of high quality and reliability based on detailed work plans and drawings for construction and installations. ‘Substantive estimates’ are developed during the design phase and used to seek effective project approval (PWGSC, 2012).
The following sections describe the five main management processes proposed to administer publicly funded capital projects, with BIM applications (Figure 5-2). Benefits of the proposed approach are described in the section 5.3.

### 5.2.1 Planning phase

As shown in Figure 5-2, prepared documents in this phase will be the same in every respect as in the traditional Design-Bid-Build method. The scope of the project and expectations of quality are established by the owner and design consultants (Procedures and Guidelines Recommended, 2012). A ‘Feasibility Study’ may be conducted to determine the preferred development options, prepare preliminary sketches, outline specifications, and, work out
‘indicative cost estimates’. An ‘indicative estimate’ is in unit cost analysis format (such as cost per square meter) and provides rough cost projection. It is used for budget planning purposes in the early stages of concept development of a project (PWGSC, 2012). Corresponding budget and schedule will then also be established to obtain financial approvals from the competent authorities.

5.2.2 Modeling phase
When the project is approved with required funding, the owner will select and engage a BIM consultant and corresponding design team to develop a ‘schematic design model’ and prepare contract documents. The BIM consultant may be an architect firm as in the D-B-B method and shall be solely responsible for all long term errors detected in the coordinated BIM model in future and the corresponding damages. These documents form the basis for the agreement between the owner and the ‘Partnering Contractor’, who is selected as the lowest bidder to participate in the design coordination of the BIM process. The owner’s BIM consultant and engineers then prepare an architectural ‘Design Model’ to the LOD-200, with 3-dimensional representation of the components, but not necessarily for other discipline-specific information linked to it. The ‘Design Model’ will contain sufficient details to produce site development plans, preliminary floor plans, all major elevations of the building(s), outline cross sections of any non-typical spaces or structural aspects, and major materials along with architectural renderings (AIA, 2012). The model may exclude items that can be adequately covered by relevant codes and/or performance specifications. At this stage, the designer has the option to develop a detailed project design using 2D CAD applications along with the BIM model. All 2D drawings, the BIM model, and specifications together with other legal documents make up the ‘Early BIM-Partnering’ contract documents, which also serve as the Request for Proposal (RFP) (Alaska Department of Education, 2004).

5.2.3 Partnering award phase
Prior to the BIM partnering sessions, a partnering contractor is selected through competitive bids from a pool of prequalified contractors. A guaranteed maximum price for construction is established at the selection. The pre-qualification procedure shall be through advertisement placed in local and national newspapers and national electronic bulletin board(s) (Fayek et al., 1999). The contractor shall commit to hire a qualified BIM design firm for the whole construction period, along with a team of qualified sub-contractors.
This contract price is fully enforceable, with no opportunity for future adjustment in price or schedule unless there is a subsequent change in the scope or design that is requested by the owner. Once satisfactory prices are obtained, the notice to proceed is given for the partnering contractor’s BIM professionals and sub-contractors to participate in the ‘Early Partnering Phase’.

5.2.4 Early BIM partnering phase
In the ‘Early Partnering Phase’ of the proposed public project procurement method, the owner’s project manager, owner’s BIM consultant, contractor’s BIM designer/engineer, and sub-contractors work together to establish a ‘Full Design Model’ for the Construction Phase. The partnering team will develop more detailed model based on the ‘Reference Model’ created in the Modeling Phase (section 5.2.2) (Richard et al. 2010). Specialty sub-contractors should develop discipline specific models independently. They should be merged with the Architectural Model to develop the integrated BIM model. The building information of each discipline-specific model should be sharable, with other discipline-specific models, for project collaboration. Design review(s) of different discipline-specific models provide data-verification and error-elimination feedbacks to ensure the accuracy of the BIM model. The model is then analyzed to assist project evaluation, reduce construction conflicts, reduce construction waste, and enhance project collaboration. Detailed design coordination is an intensive process due to many reciprocal dependencies among the designers and specialty contractors. The detailing work for each trade is dependent on information from the designers and other trade contractors. To create a collaborative work environment, detailers need to work side-by-side (with designers and trade contractors) to coordinate their designs.

5.2.5 Construction award
During the ‘Design Model Coordination’ process, the partnering team completes all detailed engineering designs and specifications in consultation with the owner’s project manager. Any remaining details of the architectural and site development designs will be completed in accordance with all applicable codes. The BIM output as a ‘Full Design Model’ at this point will be ‘frozen’ to create construction documents for the contract award. The construction documents and shop drawings prepared at this stage supplement, but do not replace the contract documents and the BIM Model prepared during the Modeling Phase. Those latter documents prevail over the construction documents in case of any disputes.
Construction contract price is predicted based on the initially prepared ‘Schematic Design Model’ and the specifications free of errors and omissions, which may not always be the case. After the completion of the ‘Full Design Model’ the owner has the right to terminate the contract by paying a previously stipulated sum to the contractor and not enter into the next level of the construction contract. The liability to pay a stipulated amount by the owner will protect the contractor from willful approach of the owner to acquire the model and perform construction with another contractor. After the acquisition of the BIM model, the owner will have full ownership rights to the BIM model created in the BIM partnering phase. The owner’s BIM consultant will be liable for any design errors and consequent damages in this situation.

The owner then administers the construction contract with the contractor. The owner’s project manager monitors the work in progress during the construction phase and authorizes monthly progress payments and final payments to the contractor.

5.3 BIM Based Partnering: Case Study

This section describes a case study which explored the practicality of the proposed ‘Early BIM Partnering’ collaborative process in a publically funded construction project. The case study was performed by working in parallel with the project team. The project was originally planned to use a traditional design-bid-build with low bid procurement. A coordinated ‘Full Design Model’ was created during the design phase by AEC design teams. The exact details and characteristics of the project will not be discussed in this paper for confidentiality reasons.

5.3.1 Project overview

The case study focused on an ‘Office and Shopping Space’ project. The planning phase of the project started in October 2010 with a feasibility survey on a 5600 square metre area, and it was scheduled to reach project completion by the end of April 2012. The new building is a five-storey reinforced concrete structure totalling around 14,000 square metres of floor area. The building complex houses customer galleries, shops, and office spaces on the first floor. It has car parks in the upper and lower ground floor levels. Planning and design for the building complex was subject to the Provincial Building Code, which sets out definitive and detailed procedures to arrive at estimates and operational issues. These guidelines prescribe accommodation requirements, communications and security levels, and details of interior
layouts, room sizes, area adjacencies, visibility, sightlines, circulation, and other spaces.

5.3.2 Project organization
The public owner had a team of administrative, architectural, mechanical, and electrical design staff to provide design and construction services for the new project. The department undertook 3 similar building projects in previous years. In addition to management and coordination of design and construction services, the engineering group was also responsible for payments and record keeping. The General Manager in the hierarchy was the owner’s authorized representative as the Project Manager. He was responsible for overall contract administration. The Engineering Manager was a registered professional ‘Site Engineer’ who mainly coordinated the ‘Early Partnering Phase’ from the owner’s side and had no previous experience in BIM solutions. The architectural firm for the project was selected in a ‘Qualification based selection’ through a publically advertised Request for Proposals (RFP).

5.3.3 The BIM initiative
A decision was made by the senior management of the public client to collaborate with the authors to pilot test the proposed BIM partnering framework in the building project to test all the possible parts of the proposed BIM framework. The architectural design firm had basic experience of using BIM and used it mainly to generate 3D visualisations. The design team included twelve staff members – a recent graduate, a CAD expert, a structural engineer, a highly experienced design detailer, and the principal consultant, who had some training in BIM Revit. One of the BIM modellers had sound CAD drafting knowledge.

5.3.4 Early partnering contract award
Selection of the General Contractor for the project was performed through a prequalification advertisement process by utilizing a standard ‘Submission of Qualification’. All qualified contractors, without limiting the number of bidders, were permitted to bid on the project. Evaluation criteria typically included the ability to deliver the construction project on the basis of specialized expertise, technical staff resources, and relevant work experience subject to reference checks. A weighted score of each contractor was calculated and contractors with a minimum score of 30 out of 50 were qualified to bid. The contract was awarded to the lowest qualified bidder. The subcontractors agreed to partner the design process using BIM tools under the ‘Design-Assist’ method, and agreed to complete coordination using 3D tools to obtain the final construction drawings.
An integrated 3D model (Revit Architecture) was made available to the tenderers to assist in better visualization of the project and for pricing purposes. It was not a formal contract document, although this is a future goal in the proposed framework.

5.3.5 Design until tender documentation

The principal consultant initially received a design brief from the client, with spatial requirements, to produce the 2D architectural model for tender documentation. The architect was responsible for the architectural and structural scope of work. As lack of trust in completeness and accuracy of 3D models had remained a major concern for the public client, it was decided that the architect would issue documents using AutoCAD without the BIM approach and then the design team would coordinate the documentation into the BIM model.

5.3.6 Coordination tools used

The main objective of the case study was to analyze the possible adoption of BIM in a public sector construction project, with an objective to produce error-free design and documentation through ECI. At present, the construction industry mostly uses the AutoCAD platform with a ‘.dwg’ file format for creating design/drawings. Thus it was decided to use Autodesk BIM products for easy exchange of data, and transition from the CAD environment to the BIM process. This also addressed the interoperability issues to some extent through the IFC file format export facility, and accommodated the specific needs of multiple disciplines in the design team. The decision was made to use following compatible modelling tools from Autodesk:

- Architecture: Revit Architecture
- Structural: Revit Structure
- Mech/Elect/Plum: Revit MEP
- Costing: Quantity Takeoff
- Clash Detection: Navisworks
- Performance Analysis: Ecotect Analysis

5.3.7 The BIM modeling process

One of the major problems that the design consultant had was to define the levels of detail. It was decided to produce models between ‘Level 200’ and ‘Level 300’ to keep the file size smaller and modelling work faster. Strategies used to balance the file size of the model without compromising the required level of details were:
1. Only typical floors were detailed
2. It relied on 2D line work for detailing anything over 1:40 scale drawing
3. Different level of details were used for different purposes (architectural detailing, for example was done up to LOD 300)

Thus, the project had a main model, used for documentation and collaboration with the project team, and other models for high-end rendering. When it came to documentation in smaller scales, parts of the main model were extracted and details were generated using 2D AutoCAD.

The BIM model was primarily intended to generate accurate and integrated 2D documentation, and allow clash detection and collaboration with the structural modeler. The initial architectural model generated by the principal consultant during contract documentation was subsequently used throughout the BIM partnering process, to generate the discipline-specific models. The modeler had only to adjust, not re-create, the model to allow accurate output of plans, details, and structural drawings. The structural engineer used the architectural model as a base for creating and analyzing the structural model. The structural engineer shared his model with the MEP engineer, so that the engineer could create a MEP model on the same design. The architect then linked both the structural and MEP models back into the original architectural model.

The following steps were taken to keep the BIM model ‘collaboration-driven’, favor 2D documentation and speedup the automatic quantities generation:

- Wall exterior lining was not drafted and referred through textual notes.
- Objects were modeled generically without defining their composition or material used.
- Sculptural details like roof facias and balusters were not modeled.

To achieve the highest level of interoperability between packages outside the Autodesk products, it was suggested to use Industry Foundation Class (IFC) on the project. Multidisciplinary collaboration using the BIM model mainly happened between the architect and the structural engineer, because of the extra time required to generate and transfer IFC files and the risk of data degradation in the process. This collaboration was further tested and
augmented by comparing the 2D-drawings generated through ‘Full Design Model’, with the contract 2D-drawings initially created by the Architect.

5.3.8 The coordination sequence
The challenges of latency in decision making and information access were addressed by collocating the design team at the client’s premises. The overall goal was to create a collaborative work environment and resolve reciprocal dependencies. The owner’s consultant issued a basic architectural model to the design consultant and sub-contractors. After linking the basic model, a collaboration mechanism was set up by the structural engineer. The ‘Copy/Monitor’ tool in Revit was used by the structural engineer to identify the changes made by the Architect to his model and vice-versa. When any updated file from a project team member was received, Revit automatically updated the link to that file.

All the discipline specific models were brought in to Navisworks by the principal consultant, and clashes were identified using the Clash Detective function in Navisworks. The process was repeated until all major clashes were resolved. The mechanical and plumbing designs were first documented in 2D CAD and then modeled in 3D, using 2D as an underlay. The primary function of Navisworks was to provide 3D model interoperability to the design team. The project team collaboratively determined the small size design brake-ups to analyze constructability, and perform clash detection through an iterative process.

5.4 Building Performance Analysis
The architectural BIM model was used to perform energy and day lighting analysis of alternate early design concepts. This was to assess the impact of various configurations on daylight levels and energy use. The model was provided with the information needed, such as surface geometry and respective UV values, reflectance, and transmittance values of the materials. The model was exported to IFC 2x2 file formats from Revit Architecture and several virtual facility options were reviewed by the design team.

5.4.1 Day light simulation
Daylight simulation stressed that windows in an extreme climate should be strategically placed for maximum daylight availability, maximum solar gains during the winter, and minimum solar gains during the summer. Figure 5-3 illustrates an initial evaluation of a schematic design concept using the ‘Ecotect’ lighting simulation and rendering system with IFC 2x2 file generated from the architectural BIM model. This image provided valuable
information during the early stages of design for selecting elevations and orientations that could provide maximum daylight gains on different surfaces of the building.

**Figure 5-3: Monthly average solar irradiance on the different surfaces**

### 5.4.2 Energy modeling

‘Ecotect’ was used to compare benefits of day lighting and energy use strategies. This study was found helpful in addressing the interoperability issue through IFC data exchange efficiency. This analysis helped to demonstrate that any use of daylight would result in net energy loss in the building, as the solar gain through windows was insufficient to make up for the energy loss through windows. The energy modeling used in the design was less than optimal, as late changes were made to the building elevations and there was indecision about the materials during the design phase.

### 5.4.3 Space conflict detection

Interference conditions of structural beams with HVAC ducts were identified by using the ‘Interference Check’ tool of Revit. Model analysis assisted in project evaluation and potentially reduced construction conflicts, construction waste, and lead to the enhancement of project collaboration. Navisworks allowed teams to automatically analyze the 3D models of different disciplines for conflicts between systems and model visualization. Initially, the architect suggested a floor-to-floor height as of 3.00 m. However, during the model coordination it was found insufficient space to accommodate the HVAC system without a conflict. Thus, the floor to floor height was increased from 3.00 m to 3.60 m during the BIM-Partnering process.
5.5 Efficiency and applicability of the BIM partnering process

The indices, that were tracked to measure the efficiency of the BIM partnering, were:

- Hours spent by the design team to prepare BIM models and coordination. It was observed that one BIM expert along with two engineers with proficiency in using drafting tool on computers (one each from the contractor and the owner spends 3 hours a day) could perform design coordination within three months period.

- Ability of the staff to handle new technology implementations. The existing staff was found capable of handling BIM technology up to a reasonable extent, though it highly depended on the learning aptitude of the individual.

- Requirements of new hardware and software in the process. The existing desktop and high end processing laptops could perform the design coordination with Revit and related Autodesk software.

- Accuracy of 2D deliverables out of the BIM model. 2D drawing could not be generated with the complete dimensions out of BIM model, and the field staff was not confident in using these drawing for fabrication at site.

- The cost planners indicated that they require much more detail in the schematic design stage if they are to fully benefit from the BIM model. Cost planners could not rely heavily on the model. There is a risk that some building objects may not completely be modeled and then counted.

- It was noted that BIM-Partnering minimized the role traditionally played by the structural engineer on such projects, and brought the steel detailers closer to being part of the project’s design team.

- The 2D deliverables, exported from ‘Full Design Model’, were not of equivalent quality to that of the traditional CAD working drawings.

- BIM-Partnering provided a forum for coordination to bring different players of fragmented design and construction industry together to address project-wide collaboration.

- BIM-Partnering helped the project team to manage client involvement by creating a coordination platform. It was aligned with the government procedures and rules.

The owner, owner’s designer, and the general contractor could contribute to the need for hardware and software requirements. One high capacity computer as ‘server’ with four moderate configuration computers was found sufficient as most of the design team members were equipped with their own desktops and laptops. Table 5-1 compares the traditional D-B-B approach with the proposed BIM partnering project delivery method.
The main emphasis of the public sector owner in the project was on the bidding principles of openness, accountability, and fairness. The author interviewed key project stakeholders to assess the applicability and satisfaction of the proposed BIM based partnering process. Interviews in two sessions of 30 minutes each were conducted with contract administration staff and multiple team members directly involved in the project planning phase and tendering process. The interview feedback suggested that the proposed BIM-Partnering procurement framework is appropriate for the public sector since the selection process is as open, fair, objective, cost-effective, and free of political influence as the traditional competitive bid method. It provides equal opportunity to every qualified firm to compete for work with innovation and flexibility.

Table 5-1: BIM Partnering v/s Traditional procurement

<table>
<thead>
<tr>
<th></th>
<th>Traditional D-B-B</th>
<th>BIM-Partnering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Hiring of Design Consultant:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selection Method</td>
<td>• Direct Selection</td>
<td>• Qualification Based Selection</td>
</tr>
<tr>
<td>Design Approach</td>
<td>• 2D CAD</td>
<td>• 2D – 3D, BIM</td>
</tr>
<tr>
<td>2) Preparation of Tender Documents:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawings</td>
<td>• 2D Designs</td>
<td>• 2D Designs</td>
</tr>
<tr>
<td>Cost estimation</td>
<td>• Substantive (Class B) using 2D drawings</td>
<td>• Substantive (Class B) using 2D Design / BIM</td>
</tr>
<tr>
<td>Level of Designs</td>
<td>• 2D detailed design</td>
<td>• Tender: 2D detailed design &amp; BIM (Level 200)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Construction: BIM (Level 300+)</td>
</tr>
<tr>
<td>3) Contractor selection:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Method</td>
<td>• Open Tender / Pre-qualified</td>
<td>• Pre-qualified</td>
</tr>
<tr>
<td>Evaluation Criteria</td>
<td>• Qualified A/E</td>
<td>• BIM capable A/E/Sub-contractors</td>
</tr>
<tr>
<td>Contract Award</td>
<td>• One step - Construction award</td>
<td>• Step 1 - Partnering award</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Step 2 – Construction award</td>
</tr>
<tr>
<td>4) Contractor’s Involvement</td>
<td></td>
<td>• During design and create BIM (Level 300+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• During construction</td>
</tr>
</tbody>
</table>

A significant improvement in the cost, value, and carbon performance can be achieved on public construction projects by ‘model analyses’ through the proposed BIM-partnering process, with early contractor involvement in the design phase. No additional design risks are assumed by the general contractor or subcontractor. The proposed method establishes a
proper balance between the complete control of the owner to choose a “most favored” contractor and the complete lack of control of the owner in the lowest bidding cost approach.

### 5.6 Summary

This section proposed a construction project procurement framework for public sector construction projects. The paper describes an approach that facilitates BIM adoption through a BIM-partnering framework and the development of a collaborative BIM model for the construction process. Specifically, the paper describes different approaches that will help project teams to overcome technical, procedural, and organizational challenges.

BIM adoption would require a change in the existing work practice. A different approach to collaborative BIM development is needed in public procurement settings where the owner is bound to work with procedural and legal frameworks. Organizations should find ways to best incorporate the existing defined process and protocols in different phases of their projects. In addition, they should assign responsibilities for design reviews and validations appropriately.

BIM model ownership challenges are well addressed by the American Institute of Architects (AIA, 2012) and additional legal measures and agreements can ensure data security and partnering-team confidence to suit varied industry needs. New dedicated roles such as ‘BIM manager’ emerged in the project teams. The BIM-Partnering procurement framework could sufficiently address legal, procurement, and cultural challenges. Though interoperability issues could be addressed using IFC data exchange method reasonably well, more detailed model parameters could not be transferred. The IFC data exchange method is still in the development stages and has yet to achieve complete interoperability through object definitions for varied BIM platforms. It is possible that data transfer becomes easier over time following improvements in software data exchange and architect’s fluency with BIM.

Even though the case study provided a structured approach to potential and willing BIM users to understand the implementation of the proposed BIM-partnering framework, further work is desired in areas such as national BIM guidelines, legal framework and project specific contractual issues. Cloud computing is a significant advancement in the delivery of information technology and services and can be broadly defined as delivering hosted IT services over the Internet (Mell et al., 2011). BIM processes created upon a cloud technology framework and integrated with a proposed procurement framework will allow construction managers to pre-plan sustainable construction by coordination and collaboration throughout
the project lifecycle.

Factors affecting BIM adoption in the areas of technical tool functional requirements and strategic issues have been evidenced in the case study. However, the implementation of the BIM-Partnering framework proved to be a necessary step in evaluating an organization’s BIM adoption capabilities, both current and potential. The evaluation revealed:

- The need for guidance on where to start, what tools are available, and how to work through legal, procurement and cultural challenges with the added technologies.
- Capabilities of project participants in BIM usage.
- Potential to move to the required BIM implementation level if not currently with such capacities.
- Training and support implications of key stakeholders.
- Lack of availability of required tools in a given project.
- Likely conflicts and risks due to change in work practices by the adoption of BIM.
Chapter 6 Conclusion

6.1 Conclusions

At present, construction waste has significant impact on the environment. Most of the waste created in construction is solid waste that ends up in landfills. Countries with limited land availabilities, like the UK, have banned landfilling completely. Construction projects are certified by LEED to encourage the diversion of waste to recycling plants. In addition, LEED encourages the use of recycled materials in building projects. Recycling creates further environmental damage in terms of indirect resource consumptions and proves to be a costly process.

The best way, then, is to avoid waste generation by adopting modern design and construction management techniques. It has been observed that a large amount of the waste created in the construction process is due to lack of design coordination and lack of involvement by the construction team in the design process. This leads to errors in construction and thereby creates costly construction changes. The overall impacts are the cost and time overruns with a considerable amount of waste generation.

Traditional project delivery methods are not capable of handling design coordination in the early project stages. All the delivery methods are merely a modification of the existing ones with a minimal change in risk allocation as per the owner’s needs.

BIM is a relatively new technology used in the design and construction process of a project. It allows the project team to coordinate design and construction processes virtually through the feedback process among the design and construction teams of varying disciplines before the start of the actual construction process. It allows team members to visualize the project in a 3D environment and suggest the necessary changes in advance of finalization of construction documentation of the project. However, BIM is not capable of handling the dynamics of the project variables.

On the other hand, SDM is the tool used in construction management to understand the complex and dynamic interactions of project variables. It can predict the dynamic behavior of the variables involved in the construction process. Though BIM has a facility to link the building objects with time (scheduling tool), it cannot analyze the interrelationships of the variables involved. Traditional costing and scheduling tools such as PERT are useful for dealing with multiple parallel and sequential activities; these are not capable of dealing with
the dynamic complexity created by interdependencies, feedbacks, and time delays. Computer models help construction managers overcome many of these limitations by experimentation through simulation under controlled conditions. The BIM process allows virtual evolution of a construction process and thus provides an opportunity to generate simulated field data over time. With this data, the SDM model becomes capable of representing the system before the start of the real construction process.

This study proved that BIM can be used as a powerful construction management tool in addition to its virtual designing and construction capabilities. However, due to the complex nature of the construction industry, its adoption is comparatively slow. Public sectors involved in the construction industry need to embrace its rapid adoption. Countries with advanced BIM adoption, like UK, Finland, USA and Australia, have targeted to make use of BIM mandatory in construction projects. To encourage widespread adoption of BIM approaches in the construction industry, a structured public project procurement framework has been proposed. The framework allows involvement of the contractor early in the design stage of the project. The case study demonstrated that there already exists an abundance of guidelines and information from other countries that can help to advance BIM adoption in real world projects.

The present study has successfully integrated BIM with SDM to minimize waste at source. The integration of BIM data into the dynamic model of the project made it possible to predict the time and cost overruns of the project and the reduction of construction waste at its source. Following are the specific conclusions of this research:

- Waste rate of linear structural components can be reduced to 0.256% by implementation of BIM technology during design.

- A more practical approach of crew-day can be used to calculate the total cost of an item of work instead of the traditional approach of using man-days and equipment cost separately.

- Traditionally, any simulation was performed by collecting the field data and the manager’s past experience. This research has demonstrated that BIM can be used as a tool to obtain the virtual data for project analysis and simulation purposes.

- Design coordination has the greatest impact on waste and construction waste can be...
reduced up to 25% at source by allowing BIM coordination early in the design phase of the project.

- When there is a change in scope of work during the construction process, final duration of the project can be forecasted with the proposed Earned Schedule methodology.

- Based on the results of the study (in Chapter 4), it can be concluded that change in scope of work has a greater impact on cost and schedule of the project than it has on waste generation.

6.2 Contributions

The key contributions of this study to the body of knowledge are the successful application of BIM and SDM in construction waste management.

1. The study introduced a novel methodology to minimize rebar waste at the project design stage by analyzing BIM models with optimization techniques. As one of the main contributors to construction waste, steel rebar waste was chosen to be the focus of this research.

2. A system dynamic model was developed to predict the construction waste at source of generation, in integration with BIM due to design changes made during the construction process.

3. A BIM-partnering framework is proposed for BIM implementation, which corroborates the smooth introduction of BIM to the existing public procurement system. It bridged the adoption gap by addressing risks, responsibilities, intellectual property, legal liability, and technical requirements through already existing global information. The proposed BIM partnering framework provided the initial ground work for developing national guidelines for wide scale BIM implementation in public construction projects.

4. A BIM model definition framework was developed to assist the model development process. This explains the evolution of BIM, defines the details contained in the model, and demonstrates its purpose and usefulness in the design and construction coordination processes.

5. A complete and practical concept of crew was proposed to analyze the resource requirements during the planning phase and in the changed construction scenarios of the
6. Earned Value management is not capable of predicting the final duration for the schedule component of the project. A method was put forth to analyze the recent technique of schedule performance, which integrates SDM and BIM to forecast the final duration of the project.

6.3 Limitations
The following are the main limitation identified in this work:

1. This work addressed the Design-Bid-Build method of construction procurement, which is generally used in public procurements. There are many other popular project delivery methods used. The involvement of contractor into the design process was studied only for public construction procurements using D-B-B procurement method.

2. Only public building projects were covered in this study with the involvement of lowest bidder only. Study could not be performed in case of refusal to enter into construction process by the lowest bidder.

3. Only linear structural components (reinforcement bars) were analyzed to demonstrate potential waste reduction abilities. Other building components may have different challenges.

4. Usefulness of BIM increases with details included in the model. Level of Details (LOD) decides the coordination level that can be achieved through virtual simulation of the construction process. The modeling process was not performed to a detailed level due to time limitations, and thus a limited amount of data was retrieved for the SD analysis.

5. Results of SDM analysis could differ with change in type, location and site conditions of the construction project. Some data were assumed based on discussions with construction managers for the analysis process.

6.4 Recommendations for Future Research
This research work can be extended to make further improvements:

1. The present work can be extended to analyze potential waste reduction through HVAC design coordination. Traditionally, mechanical/electrical/plumbing (MEP) is given the least attention during the design process, with more focus on architectural and esthetical aspects. Furthermore, quantity estimation of different components (piping and
equipment) poses a challenge to the architects. BIM can prove to be a most useful tool in the optimizing the linear waste (piping) involved in the MEP system.

2. Highways and railway track construction projects involve multiple locations with varying site conditions. Industrial construction projects, involve different aspects of design and construction. An integrated BIM and SDM methodology can be extended to infrastructural and industrial construction projects like national highways and refineries.

3. Waste optimization techniques were applied to linear components (rebar) alone, which can be further extended to 2D objects like dry wall board and wooden components. These proved to be the major contributors to construction wastes.

4. Cloud computing is a significant advancement in the delivery of information technology and services. It can be broadly defined as delivering hosted IT services over the Internet. Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction (NIST, 2011).

Waste reduction at source can be extended to BIM-server technology on infrastructure projects involved with multiple locations. Reuse of construction waste material can be achieved by coordinated BIM-server technology. BIM-Server technology allows several construction teams at several construction locations to monitor the construction process simultaneously, in a real time situation.
References


Kim, S. K. (2002).“A system development for automatic detail design and estimation of rebar work.” The 1st Year Research Rep., Gyeonggi Regional Small & Medium Business Administration, Gyeonggi, South Korea, 84–90.


Appendices

Appendix-A  Equations of the Model

Additional_Concrete(t) = Additional_Concrete(t - dt) + (additional_concrete_progress_rate) * dt

INIT Additional_Concrete = 0

additional_concrete_progress_rate = conc_apparent_productivity * conc_crew / cdelay

Additional_finishes(t) = Additional_finishes(t - dt) + (additional_finishes_progress_rate) * dt

INIT Additional_finishes = 0

additional_finishes_progress_rate = finishes_apparent_productivity * finishes_crew / fdelay

Additional_masonry(t) = Additional_masonry(t - dt) + (additional_masonry_progress_rate) * dt

INIT Additional_masonry = 0

additional_masonry_progress_rate = masonary_apparent_productivity * masonary_crew / mdelay

Additional_steel(t) = Additional_steel(t - dt) + (additional_steel_progress_rate) * dt

INIT Additional_steel = 0

additional_steel_progress_rate = steel_apparent_productivity * steel_crew / sdelay


INIT Application_level_of_BIM_technologies = 0

Applying_BIM_technologies = IF Application_level_of_BIM_technologies < Expected_level_of_applying_BIM_tech_by_decision_makers THEN existing_status_of_applying__BIM_technology ELSE 0

Application_of_Constructability_during_design_process(t) = Application_of_Constructability_during_design_process(t - dt) + (influence_on_constructability) * dt

INIT Application_of_Constructability_during_design_process = 0

influence_on_constructability = Construction_engineer_involvement_in_design / Level_of_design_complexity
bricks\textsubscript{in\_inventory}(t) = bricks\textsubscript{in\_inventory}(t - dt) + (bricks\_delivery\_rate - 
bricks\_wastage\_rate - bricks\_consumption\_rate) * dt

INIT bricks\textsubscript{in\_inventory} = 0

bricks\_delivery\_rate = ((\text{max\_bricks\_inventory\_level} - 
bricks\textsubscript{in\_inventory})/(bricks\_delivery\_delay\_time)) + bricks\_consumption\_rate + 
bricks\_wastage\_rate

bricks\_wastage\_rate = bricks\textsubscript{in\_inventory} \times masonry\_waste\_factor \times brick\_wt\_factor \times 
(1 - waste\_reduction\_rate)

bricks\_consumption\_rate = (bricks\_in\_inventory \times (1 - masonry\_waste\_factor)) / 
surplus\_bricks\_order

bricks\_Waste(t) = bricks\_Waste(t - dt) + (bricks\_wastage\_rate) * dt
INIT bricks\_Waste = 0

bricks\_wastage\_rate = bricks\textsubscript{in\_inventory} \times masonry\_waste\_factor \times brick\_wt\_factor \times 
(1 - waste\_reduction\_rate)

Concrete(t) = Concrete(t - dt) + (- concrete\_progress\_rate) * dt

INIT Concrete = 7977

cr\textsubscript{e}nt\textsubscript{e}\_progress\_rate = conc\_labour\_productivity \times conc\_crew\_month \times Schedule\_Increse

Concrete\_Change(t) = Concrete\_Change(t - dt) + (concrete\_change\_rate - 
additional\_concrete\_progress\_rate) * dt

INIT Concrete\_Change = 0

concrete\_change\_rate = fraction\_concrete\_change

additional\_concrete\_progress\_rate = conc\_apparent\_productivity \times conc\_crew / cdelay

Concrete\_in\_inventory(t) = Concrete\_in\_inventory(t - dt) + (concrete\_delivery\_rate - 
concrete\_wastage\_rate - concrete\_consumption\_rate) * dt

INIT Concrete\_in\_inventory = 0

concrete\_delivery\_rate = ((\text{max\_conc\_inventory\_level} - 
Concrete\_in\_inventory)/(concrete\_delivery\_delay\_time)) + concrete\_consumption\_rate + 
concrete\_wastage\_rate

concrete\_wastage\_rate = Concrete\_in\_inventory \times conc\_waste\_factor \times (1 - 
waste\_reduction\_rate)
concrete_consumption_rate = Concrete_in_inventory * (1 - conc_waste_factor)

Concrete_Waste(t) = Concrete_Waste(t - dt) + (concrete_wastage_rate) * dt
INIT Concrete_Waste = 0

concrete_wastage_rate = Concrete_in_inventory * conc_waste_factor * (1 - waste_reduction_rate)

Earth_Work(t) = Earth_Work(t - dt) + (- EW_progress_rate) * dt
INIT Earth_Work = 84094

EW_progress_rate = EW_productivity * EW_crew_Month

Finishes(t) = Finishes(t - dt) + (- finishes_progress_rate) * dt
INIT Finishes = 16244

finishes_progress_rate = IF Additional_Concrete = 0 THEN (finishes_crew_month * finishes_labour_productivity) ELSE ( IF Finishes <> 0 THEN 110 * finishes_labour_productivity ELSE 0)

finishes_Change(t) = finishes_Change(t - dt) + (finishes_change_rate - additional_finishes_progress_rate) * dt
INIT finishes_Change = 0

finishes_change_rate = fraction_finishes_change

additional_finishes_progress_rate = finishes_apparent_productivity * finishes_crew / fdelay

Frequency_of_conflicts_between_building_components(t) =
Frequency_of_conflicts_between_building_components(t - dt) + (- clash_detection_rate) * dt
INIT Frequency_of_conflicts_between_building_components = 75

clash_detection_rate = GRAPH(floor_area_constructed_per_month)
(100, 0.00), (200, 0.5), (300, 1.00), (400, 1.50), (500, 2.00), (600, 2.50), (700, 3.00), (800, 3.50), (900, 4.00), (1000, 5.00)

Frequency_of_design_change(t) = Frequency_of_design_change(t - dt) + (- decreasing_design_changes) * dt
INIT Frequency_of_design_change = 70

decreasing_design_changes = GRAPH(Level_of_design_complexity)
(0.00, 0.5), (1.00, 1.00), (2.00, 1.50), (3.00, 2.00), (4.00, 2.50), (5.00, 3.00)
Improvements_in_adoption_of_BIM_technology (t) =
Improvements_in_adoption_of_BIM_technology (t - dt) +
(Change_in_use_of_traditional_design_coordination_methods) * dt

INIT Improvements_on_traditional_construction_culture_and_behavior = 0

Change in use of traditional design coordination methods =
Commitment_to_Implement_BIM_in_early_design_phase

Level_of_design_complexity(t) = Level_of_design_complexity(t - dt) +
(-decreasing_complexity) * dt

INIT Level_of_design_complexity = 3

decreasing_complexity = Coordination_among_AEC

Masonry(t) = Masonary(t - dt) + (- masonry_progress_rate) * dt

INIT Masonary = 2379

masonry_progress_rate = masonry_crew_month * masonry_labour_productivity

Masonry_Change(t) = Masonary_Change(t - dt) + (masonary_change_rate -
additional_masonary_progress_rate) * dt

INIT Masonary_Change = 0

masonary_change_rate = fraction_masonary_change

additional_masonary_progress_rate = masonary_apparent__productivity * masonary_crew / mdelay

MEP(t) = MEP(t - dt) + (- MEP_progress_rate) * dt

INIT MEP = 16248

MEP_progress_rate = IF Additional_Concrete = 0 THEN (MEP_crwe_month *
MEP_labour_productivity ) ELSE ( IF MEP < > 0 THEN 64 * MEP_labour_productivity
ELSE 0)

Mixed_Waste(t) = Mixed_Waste(t - dt) + (waste_generation_rate) * dt

INIT Mixed_Waste = 0

waste_generation_rate = average_waste_generation * constructed_floor_area_monthly * (1-
waste_reduction_rate)

Productive_Concrete(t) = Productive_Concrete(t - dt) + (concrete_consumption_rate) * dt
INIT Productive_Concrete = 0

congrete_consumption_rate = Concrete_in_inventory * (1 - conc_waste_factor)

Productive_masonry(t) = Productive_masonry(t - dt) + (bricks_consumption_rate) * dt

INIT Productive_masonry = 0

bricks__consumption__rate = (bricks_in__inventory * (1 - masonary_waste_factor)) / surplus_bricks_order

Productive_steel(t) = Productive_steel(t - dt) + (steel_consumption_rate) * dt

INIT Productive_steel = 0

steel_consumption_rate = (steel_in_inventory * (1 - steel_waste_factor)) / surplus_steel_order

Schedule_Increse(t) = Schedule_Increse(t - dt) + (increase_in_schedule) * dt

INIT Schedule_Increse = 0

increase_in_schedule = adjustment to change * adjustment_fraction

Steel(t) = Steel(t - dt) + (- steel_progress_rate) * dt

INIT Steel = 1380

steel_progress_rate = IF ENDVAL(WP_Steel) < 396 THEN (steel_crew_month*steel_labour_productivity) ELSE IF ENDVAL (WP_Concrete) > 3100 AND ENDVAL(WP_Steel) >396 THEN (steel_crew_month*steel_labour_productivity ) ELSE 0

steel_in_inventory(t) = steel_in_inventory(t - dt) + (steel_delivery_rate - steel_wastage_rate - steel_consumption_rate) * dt

INIT steel_in_inventory = 0

steel_delivery_rate = ((max_steel_inventory_level - steel_in_inventory)/(steel_delivery_delay_time)) + steel_consumption_rate + steel_wastage_rate

steel_wastage_rate = steel_in_inventory * steel_waste_factor * (1-waste_reduction_rate)

steel_consumption__rate = (steel_in_inventory * (1 - steel_waste_factor)) / surplus_steel_order

Steel_Waste(t) = Steel_Waste(t - dt) + (steel_wastage_rate) * dt
INIT Steel_Waste = 0

steel_wastage_rate = steel_in_inventory * steel_waste_factor * (1 - waste_reduction_rate)

steel_Change(t) = steel_Change(t - dt) + (steel_change_rate - additional_steel_progress_rate) * dt

INIT steel_Change = 0

steel_change_rate = fraction_steel_change

additional_steel_progress_rate = steel_apparent_productivity * steel_crew / sdelay

Total_concrete_change(t) = Total_concrete_change(t - dt) + (- concrete_change_rate) * dt

INIT Total_concrete_change = 268

concrete_change_rate = fraction_concrete_change

Total_finishes_change(t) = Total_finishes_change(t - dt) + (- finishes_change_rate) * dt

INIT Total_finishes_change = 195

finishes_change_rate = fraction_finishes_change

Total_masonary_change(t) = Total_masonary_change(t - dt) + (- masonary_change_rate) * dt

INIT Total_masonary_change = 33

masonary_change_rate = fraction_masonary_change

Total_steel_change(t) = Total_steel_change(t - dt) + (- steel_change_rate) * dt

INIT Total_steel_change = 33

steel_change_rate = fraction_steel_change

WP_Concrete(t) = WP_Concrete(t - dt) + (concrete_progress_rate) * dt

INIT WP_Concrete = 0

concrete_progress_rate = conc_labour_productivity * conc_crew_month * Schedule_Increse

WP_Earth_Work(t) = WP_Earth_Work(t - dt) + (EW_progress_rate) * dt

INIT WP_Earth_Work = 0
EW\_progress\_rate = EW\_productivity \times EW\_crew\_Month

WP\_Finishes(t) = WP\_Finishes(t - dt) + (finishies\_progress\_rate) \times dt

INIT WP\_Finishes = 0

finishies\_progress\_rate = (IF Additional\_Concrete = 0 THEN (finishes\_crew\_month \times finishes\_labour\_productivity) ELSE (IF Finishes <> 0 THEN 110 \times finishes\_labour\_productivity ELSE 0))

WP\_Masonry(t) = WP\_Masonry(t - dt) + (masonary\_progress\_rate) \times dt

INIT WP\_Masonry = 0

masonary\_progress\_rate = masonary\_crew\_month \times masonary\_labour\_productivity

WP\_MEP(t) = WP\_MEP(t - dt) + (MEP\_progress\_rate) \times dt

INIT WP\_MEP = 0

MEP\_progress\_rate = (IF Additional\_Concrete = 0 THEN (MEP\_crew\_month \times MEP\_labour\_productivity) ELSE (IF MEP <> 0 THEN 64 \times MEP\_labour\_productivity ELSE 0))

WP\_Steel(t) = WP\_Steel(t - dt) + (steel\_progress\_rate) \times dt

INIT WP\_Steel = 0

steel\_progress\_rate = IF ENDVAL(WP\_Steel) < 396 THEN (steel\_crew\_month \times steel\_labour\_productivity) ELSE IF ENDVAL(WP\_Concrete) > 3100 AND ENDVAL(WP\_Steel) > 396 THEN (steel\_crew\_month \times steel\_labour\_productivity) ELSE 0

ACWP = additional\_Work\_Progress + BCWP

additional\_crew = conc\_crew + finishes\_crew + masonary\_crew + steel\_crew

additional\_Work\_Progress = WP\_additional\_Concrete + WP\_additional\_finishes + WP\_additional\_masonary + WP\_additional\_steel

average\_waste\_generation = 19 /1000

BCWP = BCWP\_Concrete + BCWP\_EW + BCWP\_Finishes + BCWP\_Masonry + BCWP\_MEP + BCWP\_Steel

BCWP\_Concrete = WP\_Concrete \times 750
BCWP_EW = WP_Earth_Work * 22.59
BCWP_Finishes = WP_Finishes * 825
BCWP_Masonry = WP_Masonry * 900
BCWP_MEP = WP_MEP * 1020
BCWP_Steel = WP_Steel * 3375

bricksrequired_per_task = 1.1
bricks_adjustment_time = 1

bricks_delivery_delay_time = bricks_adjustment_time + bricks_procurement_time
bricks_procurement_time = 1

bricks_required = additional_masonary_progress_rate + masonary_progress_rate

brick_wt_factor = 1.5
cdelay = .5
change_adj = change_monitoring / conc_crew

change_monitoring = (error_recover+fraction_concrete_change+redesign) / conc_apparent_productivity

concrete_delivery_delay_time = concrete__adjustment_time + concrete_procurement_time
concrete_procurement_time = 1

concrete_required = concrete_progress_rate  + additional_concrete_progress_rate
concrete_required_per_task = 1.1

concrete_adjustment_time = 1

conc_apparent__productivity = conc_labour_productivity*factors_effect_productivity

conc_crew = 4

conc_crew_month = concrete_planned_progress / conc_labour_productivity

conc_labour_productivity = 26.75
conc_waste_factor = .015

construction_change = Frequency_of_design_change * 3

cost_escalation_factor = 1+(Schedule_Increase) / (Planned_Duration + Schedule_Increase)

EAC = (BCWP + additional_Work_Progress) * cost_escalation_factor

Earned_Schedule = Scheduled_Progress_Months

efforts_to_reduce_waste = (effect_of_complexity_on_waste + impacts_of_conflicts_onwaste_reduction + impact_of_constructability_on_waste_reduction)

error_recover = IF TIME < 20 THEN PULSE(25, 9, 1) ELSE 0

EW_crew_Month = EW_planned__progress / EW_productivity

EW_productivity = 206

Expected_level_of_applying_BIM_tech_by_decision_makers = 50

factors_effect_productivity = effect_of_delivery_of_material * effect_of_overtime * schedule_pressure_effect*impact_of_work_space_limitation

cdelay = 1.75

finishes_apparent_productivity = factors_effect_productivity*finishes_labour_productivity

finishes_crew = 4.5

finishes_crew_month = finishes_planned_progress / finishes_labour_productivity

finishes_labour_productivity = 6

floor_area_constructed_per_month = 650

fraction_finishes__change = PULSE(40, 9, 1)

fraction_masonary_change = PULSE(10, 9, 1)

fraction_steel_change = PULSE(10, 9, 1)

fraction_to_adj = .115

Independent_Estimate_At_Completion = Planned_Duration / (IF(Schedule_Performance_Index = 0) THEN 1 ELSE Schedule_Performance_Index)
Independent_Estimate_At_Completion_Time = Time + (Planned_Duration - Earned_Schedule)/3

masonry_apparent_productivity =
factors_effect_productivity*masonry_labour_productivity

masonry_crew = 4
masonry_crew_month = masonry_planned_progress / masonry_labour_productivity

masonry_labour_productivity = 3.8
masonry_waste_factor = .01

material_on_site = 0.75
max_bricks_inventory_level = bricksrequired_per_task * bricks_required * surplus_bricks_order

max_conc_inventory_level = concrete_required_per_task * concrete_required * surplus_concrete_order

max_steel_inventory_level = steel_required_per_task * steel_required * surplus_steel_order

mdelay = 1.5
MEP_crwe_month = MEP_planned_progress / MEP_labour_productivity

MEP_labour_productivity = 10

normal_hrs_per_week = 40

Planned_Duration = 25

ratio_of_forecast_to_schedule_completion_date =
Independent_Estimate_At_Completion_Time / 25

ratio_of_material_on_site_to_material_needed = material_on_site /
theoretical_quantity_of_material_needed

ratio_overtime_hrs_to_normal_hrs_per_week = overtime_hrs / normal_hrs_per_week

redesign = IF TIME < 20 THEN PULSE(60, 9, 1) ELSE 0

Schedule_Performance_Index_Time = Earned_Schedule / (If time =0 then 1 Else time)

Schedule_Performance_Index = IF (BCWP = 0 OR BCWS = 0) THEN 0 ELSE BCWP/BCWS
Schedule_Variance = BCWP - BCWS

Schedule_Variance_Time = Earned_Schedule - time

sdelay = 1

steel_adjustment_time = 1

steel_apparent_productivity = factors_effect_productivity*steel_labour_productivity

steel_crew = 4

steel_crew_month = steel_planned_progress / steel_labour_productivity

steel_delivery_delay_time = steel_adjustment_time + steel_procurement_time

steel_labour_productivity = 10.10

steel_procurement_time = 1

steel_required = additional_steel_progress_rate + steel_progress_rate

steel_required_per_task = 1.1

steel_waste_factor = .025

surplus_bricks_order = 1.2

surplus_concrete_order = 1

surplus_steel_order = 1.2

test_overtime = 0

theoretical_quantity_of_material_needed = 1

Total_crew =
conc_crew_month+EW_crew_Month+finishes_crew_month+masonary_crew_month+MEP_crew_month+steel_crew_month + additional_crew

Total_Waste = bricks_Waste + Concrete_Waste + Steel_Waste + Mixed_Waste

work_space_available = 200
work_space_per_crew_available = work_space_available/additional_crew

WP_additional_Concrete = (Additional_Concrete) * 1000
WP_additional_finishes = ENDVAL(Additional_finishes) * 1000

WP_additional_masonry = ENDVAL(Additional_masonry) * 900

WP_additional_steel = ENDVAL(Additional_steel) * 4250

AEC_involvement_in_design = GRAPH(Impact_of_applying_BIM_technology)
(0.00, 0.00), (10.0, 1.00), (20.0, 2.00), (30.0, 3.00), (40.0, 4.00), (50.0, 5.00), (60.0, 6.00),
(70.0, 7.00), (80.0, 8.00), (90.0, 9.00), (100, 10.0)

BCWS = GRAPH(TIME)
(0.00, 0.00), (1.00, 356984), (2.00, 713968), (3.00, 1.4e+006), (4.00, 2.5e+006), (5.00,
3.6e+006), (6.00, 5.7e+006), (7.00, 7.9e+006), (8.00, 1e+007), (9.00, 1.3e+007), (10.0,
1.7e+007), (11.0, 2e+007), (12.0, 2.4e+007), (13.0, 2.7e+007), (14.0, 3e+007), (15.0,
3.3e+007), (16.0, 3.6e+007), (17.0, 3.8e+007), (18.0, 4e+007), (19.0, 4.2e+007), (20.0,
4.3e+007), (21.0, 4.3e+007), (22.0, 4.4e+007), (23.0, 4.4e+007), (24.0, 4.4e+007), (25.0,
4.5e+007)

Commitment_to_Implement_BIM_in_early_design_phase = GRAPH(waste_reduced_rate)
(0.00, 0.00), (0.1, 0.2), (0.2, 0.475), (0.3, 1.08), (0.4, 2.08), (0.5, 3.45), (0.6, 4.30), (0.7,
4.67), (0.8, 4.88), (0.9, 4.95), (1, 5.00)

concrete_planned_progress = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 517), (4.00, 333), (5.00, 526), (6.00, 526), (7.00,
636), (8.00, 569), (9.00, 569), (10.0, 723), (11.0, 723), (12.0, 687), (13.0, 175), (14.0, 651),
(15.0, 480), (16.0, 480), (17.0, 380), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00),
(22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00)

constructed_floor_area_monthly = GRAPH(TIME)
(0.00, 0.00), (1.00, 650), (2.00, 650), (3.00, 650), (4.00, 650), (5.00, 650), (6.00, 650), (7.00,
650), (8.00, 650), (9.00, 650), (10.0, 650), (11.0, 650), (12.0, 650), (13.0, 650), (14.0, 650),
(15.0, 650), (16.0, 650), (17.0, 650), (18.0, 650), (19.0, 650), (20.0, 650), (21.0, 650), (22.0,
650), (23.0, 650), (24.0, 650), (25.0, 650), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00),
(30.0, 0.00)

Construction_engineer_involvement_in_design =
GRAPH(Impact_of_applying_BIM_technology)
(0.00, 0.00), (10.0, 1.00), (20.0, 2.00), (30.0, 3.00), (40.0, 4.00), (50.0, 5.00), (60.0, 6.00),
(70.0, 7.00), (80.0, 8.00), (90.0, 9.00), (100, 10.0)

Coordination_among_AEC = GRAPH(AEC_involvement_in_design)
(0.00, 0.00), (10.0, 0.1), (20.0, 0.2), (30.0, 0.3), (40.0, 0.4), (50.0, 0.5), (60.0, 0.6), (70.0,
0.7), (80.0, 0.8), (90.0, 0.9), (100, 1.00)

effect_of_complexity_on_waste = GRAPH(construction_change)
(0.00, 0.00), (100, 1.00), (200, 2.00), (300, 3.00), (400, 4.00), (500, 5.00), (600, 6.00), (700,
7.00), (800, 8.00), (900, 9.00), (1000, 10.0)
effect_of_delivery_of_material = GRAPH(ratio_of_material_on_site_to_material_needed)
(0.00, 0.00), (0.2, 0.58), (0.4, 0.7), (0.6, 0.83), (0.8, 0.93), (1.00, 1.00)

effect_of_overtime = GRAPH(ratio_overtime_hrs_to_normal_hrs_per_week * 
(normal_hrs_per_week + overtime_hrs)/normal_hrs_per_week)
(0.00, 1.00), (0.2, 0.9), (0.4, 0.83), (0.6, 0.75), (0.8, 0.68)

EW_planned_progress = GRAPH(TIME)
(0.00, 15803), (1.00, 15803), (2.00, 15487), (3.00, 10072), (4.00, 2834), (5.00, 4486), (6.00, 4486), (7.00, 5421), (8.00, 4852), (9.00, 4852), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00)

existing_status_of_applying_BIM_technology =
GRAPH(Improvements_on_traditional_construction_culture_and_behavior)
(0.00, 0.00), (1.00, 2.50), (2.00, 5.00), (3.00, 10.5), (4.00, 19.0), (5.00, 29.0), (6.00, 45.5), (7.00, 63.0), (8.00, 80.0), (9.00, 90.0), (10.0, 100)

finishes_planned_progress = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 441), (3.00, 287), (4.00, 81.0), (5.00, 128), (6.00, 128), (7.00, 154), (8.00, 1191), (9.00, 1191), (10.0, 1640), (11.0, 1602), (12.0, 1270), (13.0, 1930), (14.0, 1203), (15.0, 888), (16.0, 888), (17.0, 702), (18.0, 552), (19.0, 552), (20.0, 275), (21.0, 275), (22.0, 433), (23.0, 216), (24.0, 216), (25.0, 0.00)

fraction_concrete_change = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 100), (10.0, 100), (11.0, 68.0), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00)

impacts_of_conflicts_on_waste_reduction =
GRAPH(Frequency_of_conflicts_between_building_components)
(0.00, 25.0), (10.0, 23.0), (20.0, 18.5), (30.0, 17.5), (40.0, 16.0), (50.0, 15.0), (60.0, 12.5), (70.0, 5.25), (80.0, 2.38), (90.0, 1.25), (100, 0.25)

Impact_of_applying_BIM_technology = GRAPH(Application_level_of_BIM_technologies)
(0.00, 0.00), (10.0, 3.00), (20.0, 7.00), (30.0, 11.0), (40.0, 14.5), (50.0, 22.0), (60.0, 30.0), (70.0, 40.5), (80.0, 56.5), (90.0, 74.0), (100, 100)

impact_of_constructability_on_waste_reduction =
GRAPH(Application_of_Constructability_during_design_process)
(0.00, 0.00), (10.0, 1.85), (20.0, 4.05), (30.0, 5.15), (40.0, 6.95), (50.0, 7.95), (60.0, 8.90), (70.0, 9.00), (80.0, 9.00), (90.0, 9.15), (100, 9.00)

impact_of_work_space_limitation = GRAPH(work_space_per_crew_available)
(5.00, 0.65), (10.0, 0.68), (15.0, 0.7), (20.0, 0.76), (25.0, 0.8), (30.0, 0.93), (35.0, 0.95), (40.0, 0.97), (45.0, 0.98), (50.0, 0.99)
masonry_planned_progress = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 123), (5.00, 608), (6.00, 608),
(7.00, 641), (8.00, 113), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00),
(14.0, 0.00), (15.0, 143), (16.0, 143), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00),
(21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00)

MEP_planned_progress = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 214), (4.00, 570), (5.00, 664), (6.00, 680), (7.00,
903), (8.00, 1062), (9.00, 1160), (10.0, 1228), (11.0, 1259), (12.0, 1399), (13.0, 1231), (14.0,
1326), (15.0, 979), (16.0, 979), (17.0, 773), (18.0, 608), (19.0, 608), (20.0, 303), (21.0, 303),
(22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00)

overtime_hrs = GRAPH(ratio_of_forecast_to_schedule_completion_date * test_overtime)
(0.00, 0.00), (0.5, 5.00), (1.00, 10.0), (1.50, 15.0), (2.00, 20.0)

Scheduled_Progress_Months = GRAPH(BCWP)
(0.00, 0.00), (1.8e+006, 3.33), (3.6e+006, 5.00), (5.4e+006, 5.83), (7.1e+006, 6.67),
(8.9e+006, 7.41), (1.1e+007, 8.09), (1.2e+007, 8.68), (1.4e+007, 9.27), (1.6e+007, 9.85),
(1.8e+007, 10.4), (2e+007, 10.9), (2.1e+007, 11.4), (2.3e+007, 11.9), (2.5e+007, 12.4),
(2.7e+007, 12.9), (2.9e+007, 13.5), (3e+007, 14.0), (3.2e+007, 14.6), (3.4e+007, 15.2),
(3.6e+007, 15.9), (3.7e+007, 16.6), (3.9e+007, 17.4), (4.1e+007, 18.6), (4.3e+007, 20.0),
(4.5e+007, 25.0)

schedule_pressure_effect = GRAPH(ratio_of_forecast_to_schedule_completion_date)
(0.00, 0.4), (0.25, 0.5), (0.5, 0.6), (0.75, 0.8), (1.00, 0.9), (1.25, 1.00), (1.50, 1.20), (1.75,
0.9), (2.00, 0.6)

steel_planned_progress = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 96.0), (6.00, 91.0),
(7.00, 110), (8.00, 98.0), (9.00, 98.0), (10.0, 125), (11.0, 125), (12.0, 119), (13.0, 69.0), (14.0,
113), (15.0, 83.0), (16.0, 83.0), (17.0, 66.0), (18.0, 52.0), (19.0, 52.0), (20.0, 0.00), (21.0,
0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00)

waste_reduction_rate = GRAPH(efforts_to_reduce_waste)
(0.00, 0.05), (10.0, 0.09), (20.0, 0.25), (30.0, 0.4), (40.0, 0.45), (50.0, 0.55), (60.0, 0.65),
(70.0, 0.55), (80.0, 0.45), (90.0, 0.35), (100, 0.2)
### Appendix-B  Table of variables used in the simulation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable type</th>
<th>Input/output</th>
<th>Units</th>
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<tr>
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<td>Canadian Dollars</td>
</tr>
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<td>Stock</td>
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<td>cubic meters</td>
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<td>additional concrete progress rate</td>
<td>Stock</td>
<td>Output</td>
<td>cum/month</td>
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<td>additional crew</td>
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<td>square metre/crewday</td>
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<td>WP Concrete</td>
<td>Convertor</td>
<td>Output</td>
<td>cubic meters</td>
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Appendix-C  Optimization Techniques

C.1 Linear optimization algorithms
In the past, optimization of rebar trim loss have been addressed as one-dimensional cutting stock problem (1D-CSP) and several algorithm based solutions have been proposed. In the current practice; CNC machines use tools which are developed based on these algorithms, to produce the required cut lengths of rebar, in the shop. Following are the widely used algorithmic approaches.

C.1.1 Linear programming (LP)
This approach was first used by Gilmore et al. (1961) to solve the trim loss problem by generating cutting patterns. A linear programming problem may be defined as the problem of maximizing or minimizing a linear function subject to linear constraints. The constraints may be equalities or inequalities. For simple example to find numbers \( x_1 \) and \( x_2 \) that maximize the sum \( x_1 + x_2 \) subject to the constraints \( x_1 \geq 0, x_2 \geq 0, \text{ and } x_1 + 2x_2 \leq 4; \quad 4x_1 + 2x_3 \leq 12; \quad -x_1 + x_3 \leq 1. \)

There are two unknowns, and five constraints. All the constraints are inequalities and they are all linear in the sense that each involves an inequality in some linear function of the variables. The function to be maximized (or minimized) is called the objective function. Here, the objective function is \( x_1 + x_2 \) (e.g. combination of rebar piece lengths).

The solution to the problem is composed of two steps (Figure C-1). The first is the search for a set of feasible combinations to be used in the second step which is the optional choice of the number of these combinations needed to satisfy the requested number of pieces.
Figure C-1: LP Combination generating algorithm for one dimensional cutting stock problem

The idea is simply to compile a large array of piece lengths in a certain order, and use this array to choose feasible combinations. This choice is carried out by using the array to add one length to the next until the accumulated length exceeds the maximum standard length. Then the number of pieces in the combination is obtained by excluding the last piece.

C.1.2 Integer Programming (IP)

In the linear-programming models decision variables are allowed to be fractional while an integer programming problem is a mathematical optimization or feasibility program in which some or all of the variables are restricted to be integers. At other times, fractional solutions are not realistic, and the optimization problem is considered (Eq. 1):

$$\text{Maximize } \sum_{j=1}^{n} c_j x_j; \quad \text{for all } i \text{ and } j \text{ as integers.}$$ (1)

and the problem is called as integer-programming problem.

The methodology used in the reduction of one-dimensional cutting wastes in the paper industry has been used to reduce the wastes of one-dimensional stocks in the construction industry (Goulimis 1990). The first step to solve this problem is to generate all feasible cutting patterns. The procedure adapted from Pierce (1964), can be used to generate all the efficient feasible cutting patterns. The next step after generating the cutting pattern is to formulate the IP model the following three steps:
(i) Decision Variables:

The next step is to assign a decision variable for each pattern that is equal to the number of times this pattern will be used in the final solution. At the end of the solution, the final values of decision variables would tell how many times each of the generated patterns should be used in order to give the minimum possible waste.

The decision variables are denoted as \( X_i \), where \( X_i \) = number of times pattern number \( i \) is used.

For example, if in the final solution, the value of \( X_4 = 5 \) and the value of \( X_9 = 8 \), the cuts that would minimize the generated waste are to use pattern Number 4 a total of five times, pattern Number 9 a total of eight times, etc.

(ii) Objective function:

The objective is to minimize the trim loss, which could be written as (Eq. 2):

\[
\text{minimize} \left( \sum_{i=1}^{I} L_{si} X_i - \sum_{i=1}^{I} C_i X_i \right)
\]

where

- \( I \) = total number of patterns generated;
- \( C_i \) = utilized length of pattern number \( i \);
- \( L_{si} \) = standard length from which pattern number \( i \) is cut.

The utilized length of a pattern is the actual useful length of the pattern where any excess or unused length would end up as scrap when using this pattern in the final solution. Thus if, for example, the pattern that has a composition of 2–3 m (utilized length=5 m) is used three times in the final solution and if the standard length used is 6.10 m, then the trim loss would be computed as \((6.10-5)\cdot3=3.3\) m that would probably end up as scrap.

(iii) Constraints:

After setting up the objective function, some constraints must be fulfilled. The constraints are simply to satisfy the demand of each length needed, which could be formulated by setting up \( N \) constraints (one for each demanded length) as follows (Eq. 3):

\[
\text{subject to} \left( \sum_{i=1}^{I} A_{ij} X_i = d_j \right) \text{ for } (j = 1-N)
\]

where
\[ A_i = \text{number of bars of length } l_i \text{ that are present in pattern number } i; \text{ and} \]
\[ d = \text{number of bars of length } l_i \text{ that are needed to satisfy the demand.} \]

Additional constraints should be set up to ensure that all the decision variables \( X_i \) are non-negative and integers \( X_i \geq 0 \) and integer \( i = 1 - I \)

### C.1.3 Sequential Heuristic Procedure

Haessler (1975) and many other solved CSP using sequential heuristic procedure (SHP) approach. Besides (finitely terminating) algorithms and (convergent) iterative methods, there are heuristics that can provide approximate solutions to some optimization problems. Gradasar et al. (1999) proposed a Sequential Heuristic Procedure (SHP) for optimising one-dimensional stock cutting when all stock lengths are different. The proposed algorithm was developed on a step by step basis. The number of basic steps equals to the number of stock lengths necessary for fulfillment of an order. At the beginning, all stock lengths belong to the set of unprocessed stock lengths. The set of processed stock lengths is empty. At each step, the set of unprocessed stock lengths is reduced by one and the set of processed stock length increases by one. Also, the number of cut pieces of particular order lengths changes, as well as the length of the processed stock length, which becomes equal to trim loss. Algorithm has the following steps:

1. Step 1: Select order lengths
2. Step 2: Select stock length and cut it with chosen order lengths
3. Step 3: If all stock lengths are not cut yet and the requirements for order lengths are not fulfilled, then go back to step 1, else stop.

### C.1.4 Genetic Algorithm (GA)

GA model was developed by O. Salem et al. (2007) and they compared it with the LP and IP models. GA is an optimization algorithm developed by John Holland (1970) based on the theories of genetics and natural selection. In genetic algorithm, a population of strings (called chromosomes), which encode candidate solutions (called individuals) to an optimization problem, evolves toward better solutions. Traditionally, solutions are represented in binary as strings of 0s and 1s. Genetic algorithms have been used to find optimal solutions for a wide spectrum of complex combinatorial problems in civil engineering where the possibility of a huge number of combinations or alternatives makes it
infeasible to examine each one of them to find an optimal solution.

C.1.5 Binary search algorithm
Sun-Kuk Kim et al.(2004) used a binary search algorithm for rebar combination based on reading rebar data file generated by automatic rebar detailing algorithm. They extracted rebar geometry data from structural design data file to estimate precise cutting lengths and quantities.

In computer science, a binary search or half-interval search algorithm locates the position of an item in a sorted array. Binary search works by comparing an input value to the middle element of the array. The comparison determines whether the element equals the input, less than the input or greater. When the element being compared to equals the input, the search stops and typically returns the position of the element.

C.1.6 Simulated annealing approach
The method of simulated annealing (Kirkpatrick et al. 1983) is a technique for optimization problems of large scale, especially ones where a desired global extreme is hidden among many, poorer, local extreme. The method has also been used successfully in designing complex integrated circuits to achieve combinatorial minimization of an objective function.

At the heart of the method of simulated annealing is an analogy with thermodynamics, specifically with the way that liquids freeze and crystallize, or metals cool and anneal. Metropolis et al. (1953) first incorporated annealing principles into numerical calculations (Eq. 4). He assumed a simulated thermodynamic system to change its configuration from energy $E_1$ to energy $E_2$ with probability

$$p = \exp \left[ \frac{-(E_2 - E_1)}{kT} \right]$$

Quantity $k$ is Boltzmann’s constant of nature that relates temperature to energy.

Following elements are provided to make use of the Metropolis algorithm

1. A description of possible system configurations.
2. A generator of random changes in the configuration; these changes are the “options” presented to the system.
3. An objective function $E$ (analog of energy) whose minimization is the goal of the procedure.
4. A control parameter $T$ (analog of temperature) and an annealing schedule which
An objective function, $E$ is created to minimize rebar waste in 1D optimization algorithm.

**C.2 Algorithm Comparison**

The 1D-CSP and different methods are reviewed by a number of researches. On construction projects, reinforcement bar are generally purchased in standard lengths and required bar lengths are normally shorter than the standard lengths with large length variations. The number of combinations of different patterns exceeds and the solution may become computationally intractable. In fact, by applying these methods, it is not easy to reliably state which of these methods is best for which problem.

LP technique is although very efficient; still might not result in the optimal amount waste due to rounding the relaxed fractional solutions to integer values. As a result, the next step would be to use Integer Programming (IP) techniques to reach an optimal integer solution. This optimization approach is not widely used because of its complexity and higher computational efforts (Gulimis 1990). When using IP techniques such as ‘branch-and-bound’, a lot of computational effort is required when the number of cutting patterns becomes too large. The ‘branch-and-bound’ approach is based on the principle that the total set of feasible solutions can be partitioned into smaller subsets of solutions. These smaller subsets are then evaluated systematically until the best solution is found. In case of reinforcement cutting stock problem, for example supply length of bar is 12.20 meter and 500 different lengths ranging from 0.5 m to 10.0 m are to be cut then the number of different patterns may easily exceed 10 or even 100 million. In that case, the solution may not be tractable. Genetic algorithms are simple to implement, but their behavior is difficult to understand, specifically for large combinatorial problems. Binary search algorithms are generally suitable for large combinatorial problems due to more computational time required. However, it is possible to use Simulated Annealing Approach method that consistently produce better results compared to others for reinforcement cutting stock problem. The results (Jahromi et al., 2011) shows the efficiency of the proposed SA method in finding cutting plans with good average values of trim losses for randomly generated problems instead of high computational times for finding global optimum with the assumptions that (i) All used stock lengths must be cut to the end in as much as it is possible and (ii) all stock lengths are identical and there is no difference between the lengths of them.
Appendix-D  Computer model of SubSystem(s)

D.1 Key map
D.3 Scope change subsystem
D.4 Material subsystem
D.5 Waste subsystem

- Concrete Waste
  - Waste generation rate
  - Constructed floor area monthly
  - Concrete wastage rate
  - Concrete consumption rate
  - Concrete waste factor

- Mixed Waste
  - Average waste generation

- Steel Waste
  - Steel wastage rate
  - Steel consumption rate
  - Steel waste factor

- Bricks Waste
  - Bricks wastage rate
  - Bricks consumption rate
  - Brick waste factor
  - Masonary waste factor

- Productive Concrete

- Productive Steel

- Productive Masonary
D.6 Waste reduction subsystem
D.7 Earned Value subsystem

- Earned Schedule
- Scheduled Progress Months
- BCWP
- BCWS
- BCWP Concrete
- BCWP MEP
- BCWP Masonary
- BCWP Finishes
- BCWP Steel
- BCWP MEP
- BCWP Finishes
- BCWP Steel
- BCWP Masonary
- BCWP Concrete
- ACWP
- EAC
- Planned Duration
- Schedule Performance Index
- Schedule Performance Index Time
- Independent Estimate At Completion Time
- Schedule Variance
- Schedule Variance Time
- Independent Estimate At Completion
- cost escalation factor
- ratio of forecast to schedule completion date
- additional Work Progress
- WP additional Concrete
- WP additional steel
- WP additional finishes
- WP additional masonry

- -
D.8 Schedule subsystem

- cost escalation factor
- Schedule Increase
- adjustment to change
- adjustment fraction
- fraction concrete change
- redesign
- error recover
- monitoring
- conc apparent productivity
- conc crew

D.9 Total Crew

- Concrete Waste
- Steel Waste
- bricks Waste
- Mixed Waste
- Total Waste

D.10 Total waste

- additional crew
- EW crew
- conc crew month
- steel crew month
- masonry crew month
- MEP crew month
- finishes crew month
- Total crew
Appendix-E  Survey Questionnaire

Building Information Modelling Survey, 2011

Thank you for agreeing to participate in this survey. The purpose of the survey is to suggest non-biased systemic model for reducing design errors and the enabling role of BIM. The survey should take approximately 10 minutes to complete. There is a section at the end of the questioner where you can leave any other comments you may have. All information received will be treated in strictest confidence and in accordance with the UBCO code of conduct.

About your Organization

Q1. Where are you doing most of your work?
   a) Canada  
   b) North America  
   c) Non North-American Country

Q2. Where are you doing most of your work?
   a) Australia  
   b) Brazil  
   c) China  
   d) Denmark  
   e) India  
   f) New Zealand  
   g) Russia  
   h) South Africa  
   i) Switzerland  
   j) UK  
   k) Other (please specify)  .........................

Q3. In what location is your office located?
   a) Alberta  
   b) British Columbia  
   c) Manitoba  
   d) New Brunswick  
   e) Newfoundland and Labrador  
   f) Nova Scotia  
   g) Ontario  
   h) Quebec  
   i) Saskatchewan  
   j) Prince Edward Island  
   k) North-West Territories  
   l) Nunavut  
   m) Yukon  
   n) Outside Canada
Q4. Approximately, how many people are employed in your organization?
   a) 1-2    b) 3-5    c) 6-15    d) 16-25    e) 26-50    f) 51-100    g) 100-200    h) 201-500    i) 500+

Q5. Approximately, how many people are directly involved in building documentation and drawing?
   a) 1-2    b) 3-5    c) 6-15    d) 16-25    e) 26-50    f) 51-100    g) 100-200

Q6. Which building industry sector best describes your work? (Check all that apply)
   a) Architect    b) Landscape Architects    c) Civil Engineers
   d) Structural Engineers    e) Other Engineers    f) Interior designers
   g) Urban designers    h) Facility management    i) Construction
   j) Contractor    k) Property management    l) Property development
   m) Local government    N) Other public sector
   O) Other (Please specify)...........................................

Q7. Which of the services does your organization offer?
   a) Project Management    b) Project drawings
   c) Contract administration    d) Full design and build packages
   e) 3D visual computer modelling    f) Tender documents
   g) Structural engineering reports and calculations
   h) Cost estimating and financial advisory services
   i) Other (please specify)..............................

Q8. What type of structures does your firm work on?
   a) Air Ports    b) Athletic structures
   c) Civil structures (Water treatment etc.)    d) Commercial Buildings
   e) Concrete residential Multi-unit    f) Educational buildings (K-12, Universities, Institutions)
   g) Health care buildings    h) Industrial (Warehouses, distribution centres)
   i) Institutional    j) Government buildings
   k) Offshore structures    l) Petroleum & Refinery structures
   m) Power and utility plant structures    n) Transportation structures (Bridges etc.)
   o) Wood residential multi units    p) Wood single family
   q) Other (Please specify)..............................

Q9. In the last 5 years, how many projects has your organization been involved in using the following procurement methods? (Check all that apply)

<table>
<thead>
<tr>
<th>Method</th>
<th>0</th>
<th>1-2</th>
<th>3-5</th>
<th>6-10</th>
<th>11-15</th>
<th>16-25</th>
<th>26+</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Fully designed projects</td>
<td></td>
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<td>b) Design and build project</td>
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<td></td>
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<tr>
<td>c) Partnering contract</td>
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<tr>
<td>d) Management contract / Construction management</td>
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<tr>
<td>e) Public Private partnership / Private initiative</td>
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</tr>
</tbody>
</table>
About you

Q10. Indicate your age group (years):
   a) < 24    b) 25~29    c) 30~34    d) 35~39    e) 40~44
   f) 45~49    g) 50~54    h) 55~59    i) 60~64    j) 65~69
   k) 70+

Q11. How many years of experience do you have in the Industry?
   a) 1~4    b) 5~8    c) 9~12    d) 13~15    e) 16~20
   f) 21~25    g) 26~30    h) 31~40    i) 41~50    j) 50+

Q12. What is your highest level of education?
   a) High School or Equal    b) Bachelors Degree
   c) Masters Degree    d) Doctorate Degree,
   e) Other (please specify)..............................

Q13. Which most closely describes your role at your firm?
   a) Drafter/Technician    b) Graduate Eng./EIT
   c) Project Eng./PEng    d) Project Manager/Sr.PM,
   e) Owner/Upper Mgmt.    f) Other (please specify)..............................

About your Company (This section is optional and confidential)

Q14. a) Name : 
    b) Company : 
    c) Phone : 
    d) Email address : 
    e) Web address : 
    f) Number of employees :

Q15. Describe the primary work tasks undertaken by your organization.

Q16. Do you use Building Information Modelling (BIM)?
    a) Yes    b) No

Q17. Are you interested in participating in a detailed BIM survey?
    a) Yes    b) No
Q18. If “No”, do you/does your organization have any plans of adopting BIM in the future?
   a) Yes  b) No

Q19. When do you think you will need to use BIM to meet your clients’ needs?
   a) Now  b) <1 Yr  c) 1-2 Yr  d) 3-5 Yr  
   e) 6-8 Yr  f) 9-10 Yr  g) 10 ++ Yr  h) Never!!!

If your answer to Q17 is “NO”; exit the survey here.

Detailed survey about BIM

Q20. How would you describe your organization’s use of BIM? (Check all that apply)

<table>
<thead>
<tr>
<th></th>
<th>For all projects</th>
<th>For the majority of projects</th>
<th>For a minority of projects</th>
<th>Don’t know</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) In one year’s time we will use BIM</td>
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<tr>
<td>b) In three year’s time we will use BIM</td>
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<tr>
<td>c) In five year’s time we will use BIM</td>
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</tbody>
</table>

Q21. Which best describes your company’s level of expertise with BIM?
   a) Beginner  b) Moderate  c) Advanced  d) Expert

Q22. Please select the BIM applications that your firm uses. (Check all that apply).
   a) Architectural  b) Structural  c) Mechanical/Electrical/Plumbing (M/E/P)
   d) 3D Modelling  e) Simulation  f) Infrastructure
   g) Plant design

Q23. Approximately, how many projects your firm has completed using BIM?
   a) Revit Family: Number! ........ b) Bentley products: Number! ........
   c) ArchiCAD products: Number! .......... d) Vectorworks Products: Number! ........
   e) Other: Number! .............

Q24. What is the single most important thing that would make your company want to adopt BIM?
   a) 3D modeling  b) Accuracy/less errors in documents / plans
   c) Better communication  d) Better quality of documents / drawings
   e) Compatibility with design process  f) Engineer requirements
   g) Early identification of conflicts  h) Improved coordination
   i) Estimates  j) Integration
   k) Improved construction processes  l) Improved code compliance
   m) Improvement in the economy  n) More accurate/easier project
   o) Waste reduction.
Q25. What is the most important way other than saving time/money that BIM is improving your company?
   a) Accurate estimate of materials/costs/time required
   b) Ease/efficiency of reviewing design / making changes
   c) Improved coordination of documents/drawings
   d) More efficient use of resources/less waste
   e) Support of green/LEED certified projects.
   f) Avoiding rework/changes
   g) Improved planning
   h) Improved presentations
   i) Improved construction process
   j) Improved scheduling
   k) Reducing errors

Q26. Which one is the greatest value of BIM you realize through its potential to:
   a) Reduce rework
   b) Reduce conflicts and changes during construction
   c) Clash detection
   d) Improve productivity
   e) Waste reduction

Q27. Do you see any potential of BIM to reduce error and rework as a significant benefit?
   a) Yes
   b) No

Q28. Is there any coordination strategy early during BIM model development stage to reduce ‘Rework’, ‘Conflicts and changes’ and ‘Error’ during construction process.
   a) Yes
   b) No

Q29. Is there any procedure followed by your organization to produce error free BIM model?
   a) Yes
   b) No

Q30. If answer is ‘Yes’, please brief the approach followed by your organization.

Q31. Do you feel any necessity of developing a systematic internal collaborative BIM process for developing ‘error-free’ model?
   a) Yes
   b) No

Thank you